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The capture and release of Trojan asteroids by the giant planets during the solar system history

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Abstract

Trojan objects can be dynamically stable over billions of years, implying that they carry precious information about the history of the solar system. We performed numerical simulations to investigate the origin and long term evolution of Trojans of the four giant planets. The results suggest all giant planets are able to capture and retain a significant population of Trojan objects from the primordial planetesimal disk after planet migration. In general, captured Trojans yielded a wide range of eccentricities and inclinations. The bulk of captured objects decay over Gyr providing an important source of new objects on unstable orbits. Our results suggest the bulk of observed Jovian and Neptunian Trojan populations are the survivors from a larger captured population, but their high-*i* component (>20°) remain unexplained so far.

1. Introduction and Methods

Trans-neptunian objects (TNOs) orbiting in the trans-neptunian belt (or Edgeworth-Kuiper belt) carry precious information about the origin and evolution of the solar system. Of the four giant planets in the solar system, only Jupiter and Neptune are currently known to possess swarms of Trojan objects, and these populations may easily surpass that of asteroids. There is evidence that the Jovian and Neptunian Trojans were mostly (or even entirely) captured from the planetesimal disk during planetary migration. However, detailed comparison of orbital distributions (i.e., eccentricities, inclinations and libration angles) with observations and investigations on the degree of (un)stability of the theoretical populations are missing. Following this reasoning, to what degree have the primordial populations of Jovian and Neptunian Trojans been dynamically depleted over the age of the solar system? How about the Trojan populations of Saturn and Uranus? What is the fate of lost Trojans?

We performed extensive dynamical simulations, including planetary migration to investigate primarily the origin and long term evolution of the Jovian and Neptunian Trojan populations. Based on the vast amount of simulation data obtained, we were able to investigate the dynamical capture of Trojans by all four giant planets from a primordial trans-neptunian disk, which were represented by particles initially placed on dynamically cold orbits. In total, we followed the orbits of more than 3 million disk particles under the gravitational influence of the four giant planets. In other series of calculations, we also investigated the stability of the Neptunian Trojan objects 2001 QR322 and 2008 LC18.

2. Main results

First, we find the likelihood of a given disk planetesimal being captured onto an orbit within Jupiter's Trojan cloud lies between several times 10^{-6} and 10^{-5}. For Saturn, the probability is found to be in the range $<10^{-6}$ to 10^{-5}, whilst for Uranus the probabilities range between 10^{-5} and 10^{-4}. Finally, Neptune displays the greatest probability of Trojan capture, with values ranging between 10^{-4} and 10^{-3}. Our results suggest that all four giant planets are able to capture and retain a significant population of Trojan objects from the disk by the end of planetary migration. The main mechanism was found to be chaotic capture, in particular during subtle mutual resonance crossings involving the host giant planet and an adjacent planet. As a result of encounters with the giant planets prior to Trojan capture, these objects tend to be captured on orbits that are spread over a wide range of orbital eccentricities and inclinations. The bulk of captured objects are to some extent dynamically unstable, and therefore the populations of these objects tend to decay over the age of the solar system, providing an important ongoing source of new objects moving on dynamically unstable orbits among the giant planets (e.g., the Centaurs and their daughter subpopulation, the short period comets) and clues to the impact regime on planets and their satellites. Considering that a huge population of objects would be displaced by Neptune's outward migration, possibly with total mass of a few tens of Earth masses, the surviving remnant of the Trojans captured during the migration of the outer planets might be sufficient to explain the currently known Jovian and Neptunian Trojan populations in the outer solar system.

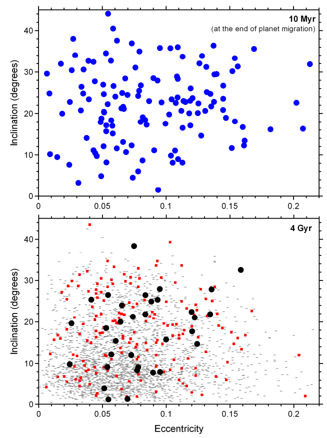

Figure 1: The orbital distribution of objects captured as Jovian Trojans once the migration of the giant planets had come to an end (top), and after following the evolution of the same system for a period of 4 Gyr (bottom). Currently known Trojans with orbits are shown in the bottom panel (taken from the MPC database). In this panel, "large" Trojans with absolute magnitudes, H, less than 10.5 are represented by squares, whilst "small" Trojans (H > 10.5) are shown as minus signs.

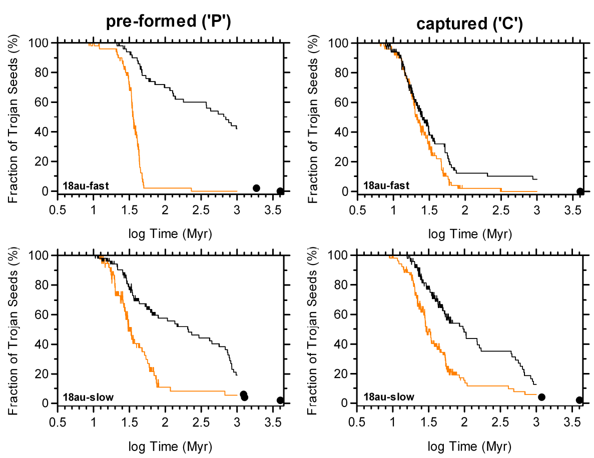

Figure 2: The survival fraction of Neptunian Trojans on billion year timescales, as modeled by seed particles obtained at the end of planetary migration. The left hand plots detail the surviving objects from the pre-formed Trojan cloud (formed insitu), and the right hand plots show those which were captured from the trans-neptunian disk (See text and Paper I for more details). The cases of fast and slow planetary migration are also shown. Trojans on tadpole and horseshoe/sub-Trojan orbits are denoted by black and orange curves, respectively. Black dots represent the approximate survival fractions.

3. Summary and Conclusions

• The four giant planets were able to capture and retain a significant population of Trojans from the primordial planetesimal disk after planet migration. These populations showed wide range of orbital properties, and capture efficiencies (tadpole orbits) of $\sim 10^{-6}$–10^{-5} (Jupiter and Saturn), $\sim 10^{-5}$–10^{-4} (Uranus) and $\sim 10^{-4}$–10^{-3} (Neptune).

• When followed over Gyr timescales, we obtained the following survival fractions for our captured populations of Jupiter and Neptune Trojans: 25% and 1-5%, respectively. However, there is a lack of $i >$ 20° surviving Trojans for both planets.

• Trojans that survived the integrations showed negligible evolution in their orbital elements, implying that the long term stability of the Trojans depends essentially on their initial orbits, probably acquired at the end of migration.

• Taken together, the lost Trojans of Jupiter and Saturn probably contained 3-10 times the current mass of observed Jovian Trojans, whilst the lost Trojan populations of Uranus and Neptune amounted tens or even hundreds times that mass! This implies that the Trojan populations have been providing an important source of objects on unstable orbits throughout the entire solar system.

• 2001 QR322 and 2008 LC18 may be evolving on unstable orbits. Future studies and observations are needed to clarify their (in)stability.

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