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太陽系におけるトロヤ群天体の軌道安定性について

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On the orbital (in)stability of Trojan asteroids in the solar system

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Abstract

Jupiter and Neptune have currently large populations of asteroids orbiting about their L4 and L5 Lagrange points, also called Trojan asteroids. Because Trojans can evolve on stable orbits with lifetimes over Gyr, the study of these objects can provide crucial insights into 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. All giant planets were able to capture disk planetesimals as Trojans at the end of planet migration. However, only 25% and 1-5% of captured Jupiter and Neptune Trojans survived after 4 Gyr of dynamical evolution, respectively, while all captured Trojan populations of Saturn and Uranus were lost during that period. In addition, a non-negligible population of observed Trojans have been leaking out from the Trojan clouds, as evidenced by the dynamical states of (1173) Anchises (Jovian Trojan), and 2001 QR322 and 2008 LC18 (Neptunian Trojans).

Key Words: solar system, Jupiter, Neptune, Trojans, asteroids, planet migration

1 Introduction

Jupiter and Neptune possess a large population of small bodies (asteroids) orbiting about the planets' L4 and L5 Lagrange points, which are located approximately at 60 deg and -60 deg in longitude from the position of the host planet, respectively (Figure 1). This configuration represents a 1:1 mean motion resonance (MMR) with the host planet. Trojans represent an unparalleled opportunity for theoretical and observational studies of small bodies in the solar system. The currently known populations of Jovian and Neptunian Trojan asteroids have been estimated to be at least as large as the intrinsic population of small bodies in the main asteroid belt![1]

Considering that the giant planets are believed to have formed from a dynamically cold disk of gas and dust (i.e., with very small eccentricities, *e*, and inclinations, *i*), one would expect that Trojans formed at the end of planet formation would move on orbits with low *e* and *i*. However, in stark contrast with the idea that Trojans formed together with their host planets, current observations of Jupiter and Neptune Trojans have revealed these objects possess wide ranges of eccentricities and inclinations, reaching almost 40 deg![2] In this way, now it is believed that the Jovian and Neptunian Trojan asteroids were captured by Jupiter and Neptune into their Trojan clouds during the migration of the planets in the early solar system.[3] As such, the observed Trojan asteroids are exciting subjects for research in planetary sciences and future space missions, as these populations likely hold the key to unveiling important details of planet migration and formation.[4]

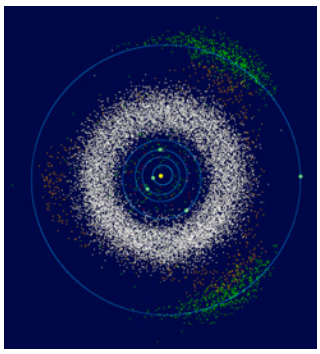

Figure 1: A view of the inner planets (four green blobs), main belt asteroids (white dots), Hilda asteroids (orange dots), and Jupiter Trojans (clouds of green dots ahead and behind the location of Jupiter, the green blob that lies at the right hand side of the

plot). Image taken from Wikipedia.

Trojan asteroids can be dynamically stable over billions of years, implying that they carry precious information about the history of the solar system. Therefore, it is important to investigate the long term stability of both theoretical and currently observed Trojan populations. In particular, we aim at answering the following motivating questions. 1. What is the origin of the Jovian and Neptunian Trojan populations? Is it capture during migration, formation in-situ, or a mix of both scenarios? 2. Whatever the main formation mechanism, did all primordial Trojans survived to this date? 3. What happened to the primordial Trojans of Uranus and Saturn? Finally, we also present the results of dynamical studies of (1173) Anchises, 2001 QR322, 2008 LC18, and 2004 KV18, since these objects displayed non-negligible unstable orbital behavior.

2 Methods

We performed numerical simulations to investigate the origin and long term evolution of Trojans of the four giant planets. First, we investigated the stability of eight Neptune Trojans (2011 HM102 was discovered recently, and thus was not modeled in our studies), and one Jupiter Trojan, (1173) Anchises. In these calculations, we created typically hundreds of clones based on the nominal best-fit orbits of these objects in order to cover their orbital uncertainties. Simulations ran for at least 1 Gyr, reaching 4 Gyr in some cases.

We modelled planet migration with an exponential decaying behaviour, where the planets moved from a pre-migration compact orbital configuration to their current orbits over ~5-50 Myr timescales, as typically detailed in the literature.[5)] The four giant planets were typically placed within ~18 or ~23 AU, with Jupiter starting at ~5.4 AU and Neptune starting at either one of the outer limits above. Two migration speeds were tested, denoted by ‘fast’ (5 Myr) and ‘slow’ (50 Myr) migration. In addition to testing the evolution of Trojans formed in-situ, we also included a primordial planetesimal disk located beyond Neptune consisting of several thousand-million test particles (Figure 2). After planet migration ceased, we followed the long term orbital evolution of the particles remaining in the system (as mostly captured Trojans of the giant planets) for at least 1 Gyr.

All small bodies started with dynamically cold orbits in the calculations, namely $e < 0.01$ and $i < 0.6$ deg. Calculations were performed with the orbital integrators EVORB[6)] and MERCURY[7)], while resonant identification of Trojans was done with the RESTICK code.[8)]

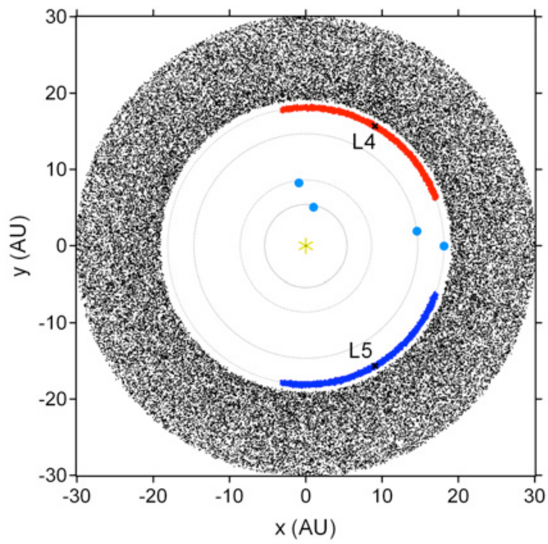

Figure 2: Representative example of the typical initial conditions used in our simulations. Objects representing the Trojans formed in situ are marked in red (L4 Lagrange point) and in blue (L5 Lagrange point), while the objects in the primordial planetesimal disk are shown in black. All particles considered were placed on initially dynamically cold orbits, with $e \sim i < 0.01$.

3 Main results

First, we discuss the results of the planet migration models. All giant planets were able to capture and retain a significant population of Trojan asteroids from the primordial planetesimal disk after planet migration[3)4)]. Although the capture probabilities were on the order of $\sim10^{-6}$–10^{-5} for Jupiter and Saturn, and $\sim10^{-5}$–10^{-3} for Uranus and Neptune, because the primordial planetesimal disk carried several Earth masses of mass, this implies that the captured Trojan populations were at least several times as more massive than the currently observed Jovian population!

In general, captured Trojans also yielded a wide range of eccentricities and inclinations, typically displaying e = 0-0.2~0.35 and i = 0-45 deg. However, as a result of this wide range of orbital elements and varied resonant states (parameters of which defined how "deep" the Trojans were trapped in the 1:1 MMR with its host planet), the bulk of captured objects decayed over Gyr providing an important source of new objects on unstable orbits (e.g., the Centaurs and their daughter family of short period comets)[9]. In this manner, our results suggest that the bulk of observed Jovian and Neptunian Trojan populations are the survivors from a larger captured population, representing approximately 25% and ~1-5% of the latter population, respectively (Figure 3)[3][10]. In contrast, since no Trojans have been observed about Saturn and Uranus to this date, the captured populations of these planets must have been lost over the age of the solar system.

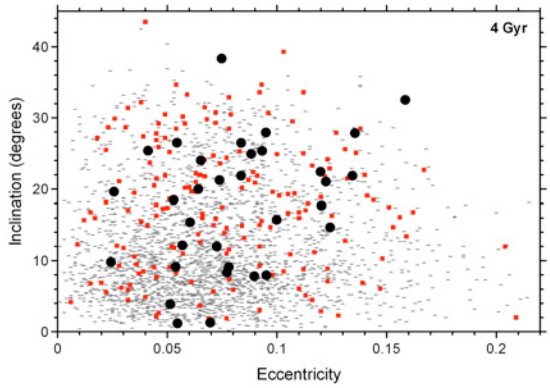

Figure 3: Orbital distribution of objects captured as Jovian Trojans during planet migration and after evolving them over 4 Gyr (shown in black circles). Currently known Trojans with more accurate orbits are shown for comparison. Large Trojans with absolute magnitudes, *H*, less than 10.5 are represented by red squares, while small Trojans (H > 10.5) are shown as gray symbols.

In addition to the population of theoretical Trojan objects that decay and leave the Trojan clouds on varied time scales, we also confirmed the existence of such "unstable" Trojan populations within the observed Jovian and Neptunian Trojan clouds.

At least three members of the Neptunian Trojan population displayed significant orbital instability. Namely, only 32, <<1, and 54% of the clones of 2001 QR322, 2004 KV18, and 2008 LC18 were able to survive the full 4 Gyr of orbital evolution, respectively. This suggests that 2001 QR322 and 2008 LC18 may be evolving on relatively unstable orbits, thus likely representing a population decaying over Gyr timescales since the early solar system.[11] On the other hand, the instability displayed by 2004 KV18 is so extreme that this object must be a recent temporarily captured Trojan object from the Centaur population[12], which consist of objects on highly unstable orbits due to their gravitational scattering by the giant planets. Figures 4 and 5 illustrate the dynamical lifetime maps of 2001 QR322 and 2008 LC18.

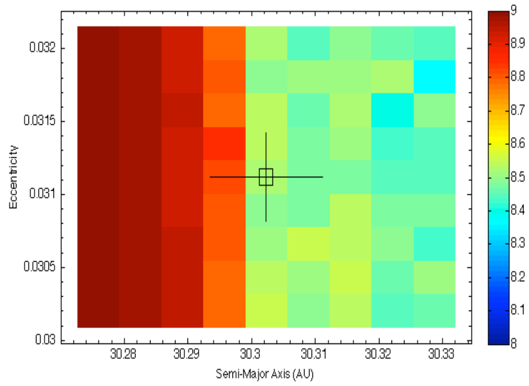

Figure 4: Dynamical lifetimes of clones of the Neptunian Trojan 2001 QR322. The legend gives the averaged lifetimes in Myr in log scale. The nominal orbit of 2001 QR322 is indicated at the center by a square, and the orbital uncertainties are shown with black bars at 1-sigma level.

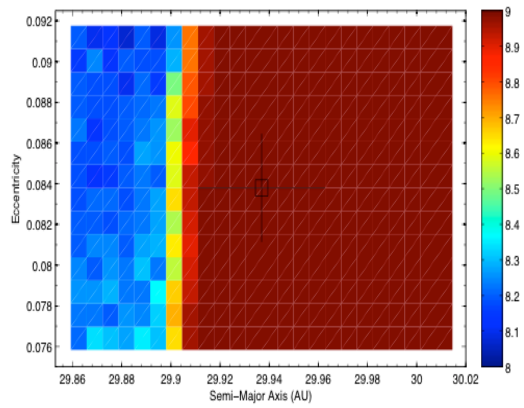

Figure 5: Dynamical lifetimes of clones of the Neptunian Trojan 2008 LC18. Symbols and notation are the same as explained in caption of Figure 4.

Although the studied Jovian Trojan Anchises has no unusual orbital properties if we consider the current orbital distribution of observed Trojans, with $e = 0.138684$ and $i = 6.913$ deg, it seems to occupy a region outside that of long term stability, according to the results on theoretical captured Jovian Trojans (Figure 3). Indeed, our results revealed that Anchises currently possesses an orbit that exhibits dynamical instability on timescales of several hundred Myr[13]. Such instability is consistent with the idea that Anchises was captured to the Jovian Trojan population during the planet's migration, thus representing one of the slowly decaying members of a ~4 times larger population of primordial Jovian Trojans. Based on our results, other observed Trojans are also expected to be evolving on a variety of stable and unstable orbits, thus these objects can provide new insights into the origin and evolution of Trojan populations, planet formation and migration, and the dynamical state of the primordial planetesimal disk. Figure 6 illustrates the dynamical lifetime map of Anchises.

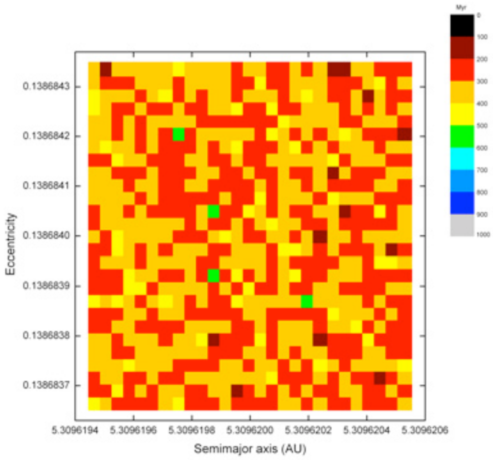

Figure 6: Dynamical lifetimes of clones of the Jovian Trojan (1173) Anchises. The legend gives the averaged lifetimes in Myr. The nominal orbit of Anchises is located in the middle of the plot (not indicated by symbols).

It is also worth noting that Anchises has quite peculiar physical properties. We used archival observational data taken by the IRAS, Akari and WISE satellites to create a thermophysical model for Anchises. We found that it is likely an object of dimensions 170 x 121 x 121 km. It is also one of the solar system's darkest objects, with an albedo of 0.027. Finally, its thermal inertia is remarkably high, between 25 and 100 $Jm^{-2}s^{-0.5}K^{-1}$, one of the largest values measured for any object at such a heliocentric distance.

4 Conclusions

The main results and implications are summarized below.

1. The four giant planets captured and retained large populations of Trojans after planet migration. These populations showed $e < 0.35$ and $i < 45$ deg, and capture efficiencies of ~10^{-6}–10^{-5} (Jupiter and Saturn), ~10^{-5}–10^{-4} (Uranus) and ~10^{-4}–10^{-3} (Neptune).

2. The bulk of captured Trojans of the four giant planets decay over Gyr. The survival fractions were 25% and 1-5% for Jupiter and Neptune, while Saturn and Uranus Trojans were probably entirely lost.

3. Anchises, 2008 LC18, and other unstable Trojans likely represent evidence that primordial captured Trojan populations have been slowly decaying over the age of the solar system.

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