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The Formation of Neptune Trojans under a Planetary Instability Migration Model

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Abstract

A numerical integration of the equations of motion of the four giant planets and a disk of $\sim 3\times10^4$ planetesimals is done. The planetesimals have mass to perturb the planets but not themselves. In this integration, the planets experience a phase of close encounters (Nice Model). During the integration some planetesimals are trapped into the 1:1 mean motion resonance with Neptune, but all escape until the end of the integration. I do five cloned integrations using the same migration rates of the planets as determined by the original integration, and also including 200 clones of all temporary trapped planetesimals as Neptune Trojans. In the end of this new integration some planetesimals are still in the 1:1 mean motion resonance with Neptune. From the model I estimate the mass of the Neptune Trojans at around $3 \times 10^{-4} M_\oplus$ and inclinations up to $50°$.

1. Introduction

A peculiar feature of Neptune Trojan orbits is their wide range of inclination distribution [2]. Also, the total number of these 1:1 resonators is estimated at around 150 with $H_r \leq 10.0$ [1]. I investigate the process of production of Neptune Trojans in a model of planetary migration with close encounters with the planets (Nice model [3]). Although considering around 3×10^4 particles in the original integration, no particle survives to the end of the integration as Neptune Trojan, although many of them are temporarily trapped. This is in fact expected since as the planetesimals disk's mass is estimated at $35M_\oplus$, each particle in the simulated disk carries around $10^{-3}M_\oplus$. This is the estimated mass of the cold Kuiper belt [4], which is likely at least one order of magnitude larger than the Neptune Trojans mass. Thus I redo the original integration five times using only cloned particles from the trapped Trojans, as explained in the next Section.

2. The Numerical integrations

I mimic five times the original integration, keeping the same migration rate of the planets but changing the initial conditions so that the planets stop as close as possible to their present distance from the Sun. During each of these new integrations I place 200 clones of each temporarily trapped Trojan from the original integration. Since in the replayed integrations the planets have different orbital elements from the original ones (only the migration rate is maintained), the clones are produced with a normalized semi-major axis with respect to the corresponding Neptune from the new integrations. Eccentricities and inclinations are the same as the original ones, and the other angles are the same relative to Neptune's mean longitude. Clones are introduced at about the mean time of evolution of the Neptune Trojans in the original integration. Temporary Neptune Trojan captures in the original integration will be considered for cloning and introducing in the five test integrations whenever the particle is kept as Neptune Trojan continually for at least 10 My. In the end of each of the five integrations, I check the surviving Trojans and analyze their orbital distribution and the total number of objects left as Neptune Trojans, what allows the estimation of their mass.

3. Results

Figure 1 shows the cumulative inclination distribution considering all five integrations. We notice that most of the inclinations are in the range $10°$ to $30°$ with a few below $10°$ and above $30°$. The highest inclination is $51.2°$ and the lowest one $2.4°$. These numbers are well in accord with estimated distributions of Neptune Trojans [2]. Also the libration widths distribution looks compatible with an estimated real distribution [2]. The total mass of Neptune Trojans estimated from the five integrations range from 1.5×10^{-4} to $4.5 \times 10^{-4} M_\oplus$, which seems a little too large. I noticed however that the number of Trojans in the end of the integration is quite sensible to the mean motion ra-

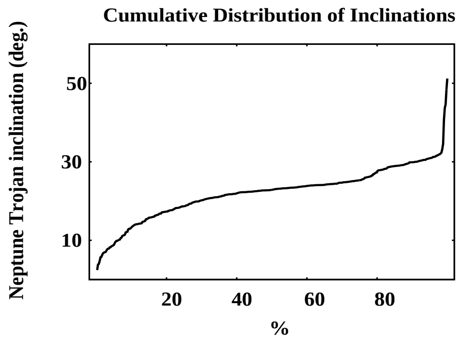

Figure 1: Cumulative Distribution of Neptune Trojans inclinations as determined by the five cloned integrations.

tio between Neptune and Uranus. When it approaches 2 the number of Trojans drops drastically. The original integration in fact suggests that although Neptune and Uranus migrated divergently most of the time, during some lapses of time the migration turned to convergent. This could even happen near the end of the integration, suggesting that Uranus and Neptune may have been a little closer to their 1:2 mean motion commensurability during the last $\sim 1Gy$.

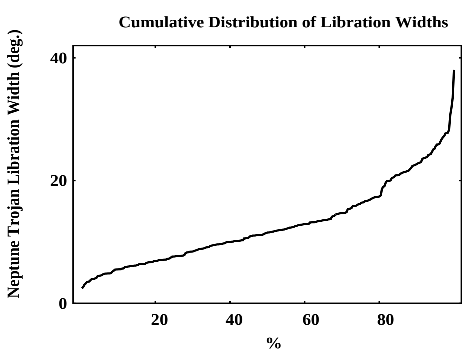

Figure 2: Cumulative Distribution of Neptune Trojans libration widths as determined by the five cloned integrations.

4. Summary and Conclusions

Numerical integrations of the equations of motion of the four giant planets and a disk of planetesimals in a case where the planets experience close approaches show temporary trappings of planetesimals into the 1:1 resonance with Neptune. These Trojans however fail to survive until the end of the integration. I run five other cloned runs from the original one, keeping the same migration rates of the planets and cloning the Trojans 200 times. Other particles are not considered in these synthetic integrations. In the end of the integrations some Neptune Trojans survive. The distribution of inclinations and libration widths are well compatible with recent results of estimation of these orbital elements from the observations [2]. I can also estimate a mass distribution for the Neptune Trojans between 1.5×10^{-4} to $4.5 \times 10^{-4} M_{\oplus}$, which is of the order of magnitude of the cold Kuiper belt mass [4]. On the other hand, Neptune Trojans population seems to be much less numerous than Kuiper Belt populations [1]. I suggest that Neptune and Uranus were a little closer to their 1:2 commensurability in the past, what is suggested by some Nice model numerical integration. This may have destabilized several Trojans producing a smaller total mass in the end. These results also reinforce the idea that the original planetesimals disk was pre-heated prior to (or heated by) Neptune's migration [2].

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