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The origin of the high-inclination Neptune Trojan 2005 TN_{53}

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ABSTRACT

Aims. We explore the formation and evolution of the highly inclined orbit of Neptune Trojan 2005 TN_{53}.
Methods. With numerical simulations, we investigated a possible mechanism for the origin of the high-inclination Neptune Trojans as captured into the Trojan-type orbits by an initially eccentric Neptune during its eccentricity damping and rapid inward migration, then migrating to the present locations locked in Neptune's 1:1 mean motion resonance.
Results. Two 2005 TN_{53}-type Trojans out of our 2000 test particles were produced with inclinations above 20°, moving on tadpole orbits librating around Neptune's leading Lagrange point.

Key words. methods: numerical – celestial mechanics – minor planets, asteroids – solar system: formation

1. Introduction

Trojan asteroids are small objects that share the semimajor axis of their host planet. They orbit the Sun with the same period as the planet and are said to be settled in the planet's 1:1 mean motion resonance (MMR). These Trojan asteroids evolve near two triangular Lagrange points, leading (L4) and trailing (L5) the planet by about 60°. At the time of writing, four Neptune Trojans have been found in the L4 region. Three of them are moving on the near-circular orbits with low inclinations. The fourth Trojan, assigned 2005 TN_{53} whose discovery was recently reported by Sheppard & Trujillo (2006), has a particularly interesting orbit for its high inclination ($i \sim 25°$). This highly inclined Trojan may have some potential implications for the early history of the outer Solar system.

Up to now, various mechanisms have been invoked to explain the formation and evolution of Neptune Trojans (see Sheppard & Trujillo 2006, and references therein). In this paper, we investigate one possible capture mechanism for the origin of such high-inclination Neptune Trojans. We numerically simulate the orbital evolution of 2005 TN_{53} in Sect. 2, and the capture mechanism is investigated in Sect. 3. The conclusions and discussion are given in Sect. 4.

2. Evolution of the observed 2005 TN_{53}

The currently best-fit orbital elements of 2005 TN_{53} are given in Table 1 (S. Sheppard, personal communication), in the heliocentric frame referred to the J2000.0 ecliptic plane at epoch 2005 October 7. In our numerical simulation, the Solar system consists of the Sun and four Jovian planets, with the masses of four terrestrial planets added to the Sun. The planets' masses, initial heliocentric positions, and velocities are taken from DE405 (Standish 1998) with epoch 1969 June 28. First, we transform the positions and velocities of four Jovian planets from the mean equatorial system to the J2000.0 ecliptic system. Then we integrate Jovian planets to the epoch 2005 October 7, using a 19th-order Cowell prediction-correction algorithm (PECE) with a time step of 10 days (Huang & Zhou 1993; Wan & Huang 2001). Next we put 2005 TN_{53} into the model and transform the ecliptic system to the invariable plane system. Finally, we compute the orbital evolution of 2005 TN_{53} with the swift_rmvs3 symplectic integrator (Wisdom & Holman 1991; Levison & Duncan 1994) up to 1 Gyr. We use a time step of 1 year, which is about 1/12 of the shortest orbital period (Jupiter) in our system.

Table 1. Orbital elements of 2005 TN_{53} in heliocentric frame referred to the J2000.0 ecliptic plane at epoch 2005 October 7. The uncertainties at the 3 σ level in a, e, i are ± 0.1 AU, ± 0.01, and ± 0.1°, respectively.

a (AU)	e	i (°)	Ω (°)	ω (°)	M (°)
30.05	0.069	25.06	9.28	90.02	276.47

Figure 1 shows the evolution of the semimajor axis a, eccentricity e, inclination i, and critical argument $\phi = \lambda - \lambda_N$ (λ is the mean longitude, the subscript N refers to Neptune) of 2005 TN_{53}. It shares Neptune's semimajor axis and moves on a tadpole orbit librating around the L4 point. The libration of ϕ centers on $\phi_c \approx 61°$ with an amplitude $\Delta\phi = \phi_{max} - \phi_{min} \approx 40°$ and a period of about 9500 years.

Considering the uncertainties of 2005 TN_{53}'s orbital elements in a, e, and i, we computed a few orbits within the error space for 10^8 years. For all these test orbits, 2005 TN_{53} librates around Neptune's L4 point throughout the integration time. Indeed, Nesvorný & Dones (2002) find that the majority of Neptune Trojans with $e \leq 0.08$, $i \leq 35°$ and amplitudes $\Delta\phi < 60°$–$70°$, like 2005 TN_{53}'s trajectory, can survive over the age of the Solar system.

3. Possible origin of high-inclination Trojans

3.1. Captured into the Trojan-type orbits

A series of numerical simulations show that the Jovian planets might experience orbital migrations due to their interactions with the remnant planetesimal disk in the primordial Solar system. Neptune, Uranus, and Saturn gain orbital angular momentum and migrate outwards, while Jupiter moves sunward as the ultimate source of the angular momentum and energy.

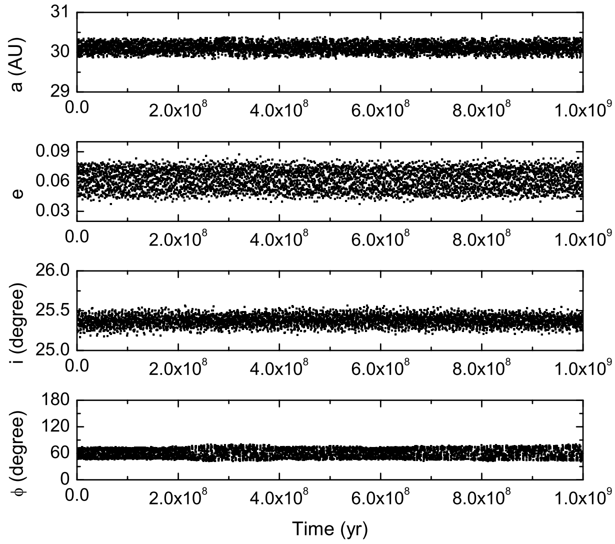

Fig. 1. Evolution of the semimajor axis a, eccentricity e, inclination i, and critical argument $\phi = \lambda - \lambda_N$ of the high-inclination Neptune Trojan 2005 TN_{53}.

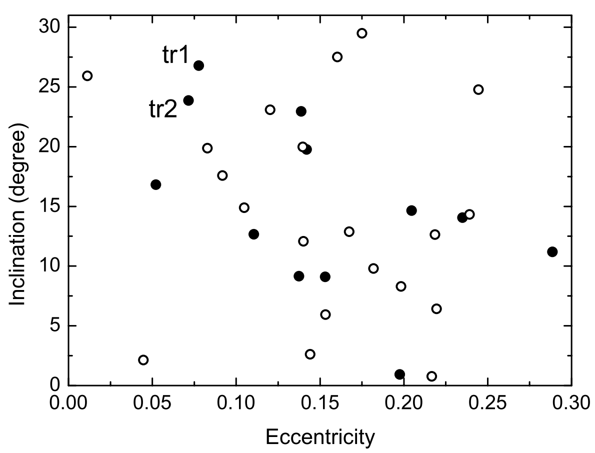

Fig. 2. The eccentricities and inclinations of the captured Trojans for the case $\tau_{\rm dump} = 2 \times 10^5$ years. Only those with librating amplitudes $\Delta\phi < 75°$ are shown. The filled circles stand for Trojans librating around Neptune's L4 point, and the open circles around the L5 point.

This migration is usually believed to progress on a timescale of $O(10^7)$ years (Fernández & Ip 1984; Hahn & Malhotra 1999).

Chiang et al. (2003) suggest that Neptune Trojans may not be captured by the outwards migratory Neptune's 1:1 MMR. During this relatively slow migration, the planetesimals have either been captured by preceding MMRs, such as the 2:1 and 3:2 resonances, or been scattered away, leaving nothing for the subsequent 1:1 resonance. Therefore, Neptune Trojans may have existed prior to Neptune's outward migration and been locked in Neptune's 1:1 MMR in their subsequent evolutions.

It is possible that Neptune's orbit was more eccentric than its current orbit in the early stages of the Solar system before the usual radial migration of Jovian planets. A high eccentricity could be the result of encounters with Jupiter and/or Saturn (Thommes et al. 1999; Tsiganis et al. 2005), or of the fact that Neptune is temporarily trapped in a MMR with a hypothetical massive planetary embryo or one of the other planets (Morbidelli & Levison 2004). By the dynamical friction due to the planetesimal disk, Neptune's eccentricity is damped in less than 10^6 years. A byproduct of this eccentricity damping process is a quick decline in the semimajor axis of several AU due to energy dissipation (Thommes et al. 1999). Here, we explore the effects of such a rapid migration of Neptune on the capture of Trojans. Although this mechanism is delicate and would need very careful simulating, in our numerical experiment of this paper, we simply assume a time variation of Neptune's eccentricity as:

$$e(t) = e_{\rm i} \exp(-t/\tau_{\rm damp}), \tag{1}$$

where $e_{\rm i}$ is the initial eccentricity, $e(t)$ the eccentricity at epoch t, and $\tau_{\rm damp}$ the eccentricity damping time-scale.

Since we focus on Neptune Trojans, we neglect the effects from Uranus by removing it from our numerical model, just as Morbidelli & Levison (2004) did. As a byproduct, the difficulty of close encounter between an eccentric Neptune and Uranus is avoided. Therefore, the Solar system now consists of the Sun, Jupiter, Saturn, and the eccentric Neptune. We model the eccentricity damping and rapid inward migration of Neptune by adding an artificial force on it along the radius vector $\hat{\boldsymbol{r}}$:

$$\Delta\ddot{r} = -\frac{2\boldsymbol{r}\cdot\boldsymbol{v}}{\tau_{\rm dump}} \cdot \frac{\hat{\boldsymbol{r}}}{r}, \tag{2}$$

where $\boldsymbol{r}$ and $\boldsymbol{v}$ are Neptune's heliocentric positions and velocities. The initial eccentricity of Neptune is set to 0.3, within the range proposed by Thommes et al. (1999). The initial semimajor axes are assumed to be 5.4, 8.7, 23.2 AU, respectively, for Jupiter, Saturn, Neptune (Malhotra 1995). The other initial orbital elements are chosen to be the currently observed values (Standish 1998). The system is in the heliocentric frame referred to the invariable plane. The linear perturbation theory gives the estimate of the magnitude of orbital migration related to the decrease in the eccentricity of a planet (e.g. Murray & Dermott 1999):

$$\ln(a_{\rm f}/a_{\rm i}) = e_{\rm f}^2 - e_{\rm i}^2, \tag{3}$$

where $a_{\rm i}$ and $a_{\rm f}$ indicate the initial and final semimajor axes of the planet. When Neptune's eccentricity is damped from 0.3 to the current value $\sim O(10^{-3})$, its semimajor axis shrinks from 23.2 AU to about 21 AU.

In addition, the eccentricities and inclinations of Trojans cannot be modified significantly by Neptune's migration of several AU (Yu & Tremaine 2001; Chiang et al. 2003). Hence, Trojan 2005 TN_{53} may have possessed a high inclination before it was hijacked into Neptune's 1:1 MMR and conserved its inclination after that. With this in mind, we consider a hot disk of 1000 test particles distributed from 20.5 to 23.5 AU: initial e and i are chosen randomly in the range 0–0.1 and 0–30°, respectively. This initial (e, i) space approximately covers the same volume as the observed Trojans' (Morbidelli et al. 2005). All other angles of an orbit (longitude of ascending node Ω, longitude of perihelion ϖ, and mean longitude λ) are chosen randomly in the range 0–2π.

We numerically simulate these processes with $\tau_{\rm dump} = 2 \times 10^5$ and 3×10^5 years. The swift_rmvs3 symplectic integrator is employed to integrate the system for 2×10^6 years. With these $\tau_{\rm dump}$, Neptune is forced to achieve a nearly circular orbit in less than 10^6 years. This eccentricity dumping time is consistent with the results obtained by Thommes et al. (1999) from a more sophisticated and hence more realistic model. In our numerical simulations, we discard the test particles that entered a Hill sphere radius of any planets.

We regard a test particle as a captured Trojan if its semimajor axis $a \approx a_{\rm N}$ and the critical argument ϕ librates. Figure 2 shows the eccentricities and inclinations of the captured Trojans at the end of numerical integration for the case $\tau_{\rm dump} = 2 \times 10^5$ years. There are two 2005 TN_{53}-type Trojans (tr1 and tr2, see Fig. 2)

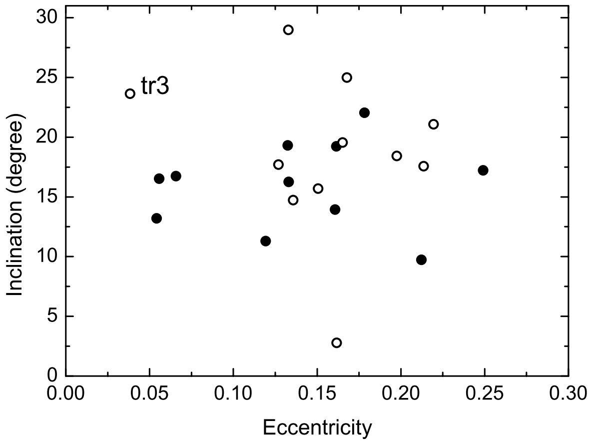

Fig. 3. As in Fig. 2, but $\tau_{\mathrm{dump}} = 3 \times 10^5$ years.

with $i > 20°$ and $e < 0.1$, librating around Neptune's L4 point. The total number of the test particles trapped in the Trojan region is 32, indicating a capture rate ∼3%. By carefully checking the orbits of these trapped Trojans, we find that (1) Neptune's 1:1 MMR starts to capture test particles as soon as the inward migration begins, despite Neptune's high eccentricity; (2) some Trojans' eccentricities are stirred up before the captures, as large as 0.3. Therefore Uranus, which was removed in our simulation, may strongly affect the stability of these highly eccentric Trojans (Gomes 1998); (3) Trojans' inclinations have no significantly change throughout the integration time; (4) the high-inclination ($i > 5°$) test particles are more likely to survive, then be captured as Trojans when Neptune sweeps through; (5) of these Trojans, 12 reside in L4 region and 20 reside in L5 region.

Figure 3 shows the case $\tau_{\mathrm{dump}} = 3 \times 10^5$ years. The capture efficiency reduces to ∼2%. In comparison with the short τ_{dump} case, a distinguishable difference is the deficit of Trojans in the region $e < 0.1$. This might be due to the relatively longer time gravitational perturbation of the eccentric Neptune. However, there is only one Trojan tr3 with $i > 20°$ that exists in this region; but unlike 2005 TN_{53}, it inhabits the L5 region. As we show in the next section, it is interesting that this Trojan tr3 will transfer to the L4 region during Neptune's outward migration to its current orbit.

Although it is unlikely to be true and it is beyond the (e, i) range of the observed Trojans, we also examined some test particles with larger initial eccentricities ($0.1 < e < 0.2$) and higher inclinations ($30° < i < 40°$). The results show that they can also be captured, and the capture probability is comparable to the above low e and i cases. However, Neptune Trojans can enjoy dynamical stabilities with $e \leq 0.08$ and $i \leq 35°$ over the age of the Solar system (Nesvorný & Dones 2002). Hence, we make no further exploration of even eccentric or inclined Trojans.

Thus far, the initial eccentricity of Neptune has been assumed to be 0.3 in all runs. We also examine other starting eccentricities of Neptune e_i^N=0.1, 0.2, 0.4 (an even higher value is unlikely to happen). We find that Neptune's ability to capture test particles into the Trojan-like orbits, in the process of the rapid inward migration, is not sensitive to its starting eccentricity. However, this migration is closely related to the eccentricity damping as we mentioned in the foregoing section; i.e., the size of orbital shift is a function of Neptune's starting eccentricity as described in Eq. (3), so that a smaller e_i^N leads to less capturing because much a narrower region would be swept through by Neptune in this case. On the other hand, a little eccentric Neptune will not suffer significant eccentricity damping; therefore, no significant energy dissipation will happen, thus the scattering with planetesimals could dominate its orbital evolution and it will migrate slowly outwards. As proved by Chiang et al. (2003), Neptune will hardly trap Trojans in this slow migration.

Table 2. The final trajectories of Trojans tr1 and tr3.

Name	a (AU)	e	i (°)	ϕ_c (°)	$\Delta\phi$ (°)
tr1	29.97	0.058	23.45	68	77
tr3	29.97	0.069	24.30	61	28

3.2. Migrating to the present locations

After the orbit is circularized, the orbital evolution of Neptune changes to a new regime, in which it migrates outward at a relatively slower speed (Fernández & Ip 1984; Hahn & Malhotra 1999). Kortenkamp et al. (2004) propose that the survivability of Neptune Trojans is ∼5% during this radial migration of Jovian planets. We investigated this usual migration process by performing a second simulation, in which the planetary orbital migration was modelled by adding an additional "drag" force on each planet along the direction of the orbital velocity $\hat{v}$, as (Malhotra 1993, 1995; Zhou et al. 2002):

$$\Delta\ddot{\boldsymbol{r}} = \frac{\hat{v}}{\tau_{\mathrm{mig}}} \left\{ \sqrt{\frac{GM_\odot}{a_{\mathrm{i}}}} - \sqrt{\frac{GM_\odot}{a_{\mathrm{f}}}} \right\} \exp\left(-\frac{t}{\tau_{\mathrm{mig}}}\right), \qquad (4)$$

where τ_{mig} is the migration time-scale, chosen to be 2×10^7 years (Li et al. 2006). The initial orbital configuration of the planets and Trojan-type companions of Neptune were those obtained from the previous simulations. We integrated the system for 2×10^8 years.

We found that during the migration, about 70% of the Trojans leak out of the 1:1 resonance and are scattered away by Neptune. And Trojans with large eccentricities $e > 0.2$ are more susceptible to loss, showing no visible correlation with their inclinations. Nevertheless, tr1 (see Fig. 2) and tr3 (see Fig. 3) survive to the end of integration. These two Trojans' orbits are very similar to 2005 TN_{53} with $i > 20°$ and $e < 0.1$, librating around Neptune's L4 point. Table 2 displays their final trajectories, in which a, e, i have been averaged over the last 2×10^6 years in the integrations. Note that the values in this system, referred to the invariable plane, are somewhat different from those given in Table 1.

Figure 4 shows the evolution of tr1. During the outward migration, tr1 is locked in Neptune's L4 region all the time, and its e and i show no significant change as predicted by Chiang et al. (2003). Figure 5 illustrates Trojan tr3's evolution. It is originally librating around Neptune's L5 point on a large tadpole orbit. At the very beginning of migration, tr3 escapes the L5 region and goes into the L4 region via the horseshoe orbit in less than 2.4×10^6 years. After tr3 enters Neptune's L4 region, its subsequent evolution is essentially like tr1's.

4. Conclusions and discussion

A high-inclination Neptune Trojan 2005 TN_{53} was newly discovered by Sheppard & Trujillo (2006). We numerically integrate its trajectory and find that the motion is stable at least 1 Gyr on a tadpole orbit librating around Neptune's L4 point and that the libration centers at about 61° with an amplitude of 40° and a period of about 9500 years.

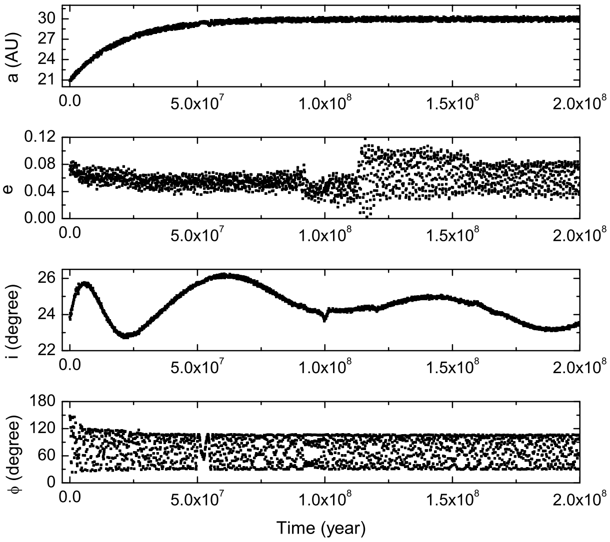

Fig. 4. Evolution of a, e, i, and ϕ of Trojan tr1 during the outward migration.

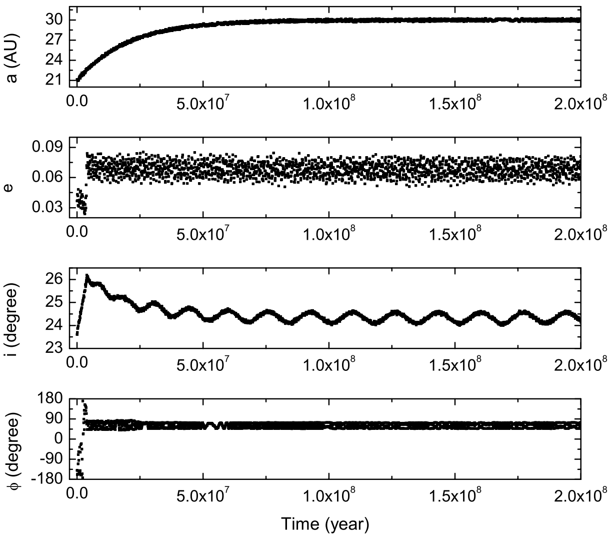

Fig. 5. As in Fig. 4, but for Trojan tr3.

Neptune might be on a more eccentric orbit than its current one in the primordial Solar system. The high eccentricity could be quickly obtained from encounters with Jupiter and/or Saturn, or it could be temporarily trapped in an MMR with a hypothetical massive planetary embryo or one of the other planets. These violent processes also "throw" Neptune into a new region (Thommes et al. 1999; Morbidelli & Levison 2004; Tsiganis et al. 2005), so the region around the eccentric Neptune was densely populated by small planetesimals. Owing to gravitational interactions with these objects, Neptune evolves into a nearly circular orbit and quickly migrates inwards of several AU in less than 10^6 years (Thommes et al. 1999). During this rapid migration, a few originally high-inclination test particles are trapped in the Trojan-type orbits as the candidates of 2005 TN_{53}. Note that the whole process above should occur in a very short phase, or else test particles would be cleared away before Neptune's 1:1 resonance arrives. In addition, this capture mechanism has less to do with the initial e and i of the Trojans or with the eccentricity of Neptune at the moment of capturing.

In the subsequent evolution of the usual radial migration of Jovian planets (Fernández & Ip 1984; Hahn & Malhotra 1999), two candidates generated via the above process migrate to the present locations near 30.1 AU locked in Neptune's 1:1 MMR. They move on highly inclined orbits ($i > 20°$), librating around Neptune's L4 point with small amplitudes. These final orbits are very similar to 2005 TN_{53}'s.

In fact, the key point in this Trojan capture mechanism is the migrating speed. As long as the migration is fast enough, its 1:1 MMR can seize Trojans, no matter how eccentric its orbit is. But if Neptune is initially on a circular orbit, interactions with the debris disk of small planetesimals will make it drift outwards with a long migration time-scale of $\mathcal{O}(10^7)$ years (Fernández & Ip 1984; Hahn & Malhotra 1999). Chiang et al. (2003) show that Neptune Trojans could not owe their existence to such a slow migration of Neptune.

To simplify our model, we have removed Uranus in our simulations, which may cause the instability of Neptune Trojans (Gomes 1998). However, Uranus does exist and may affect the evolution of Neptune Trojans. We performed a simulation that included Uranus located at 14 AU, external to the 2:1 MMR of Saturn, with $\tau_{\rm dump} = 2 \times 10^5$ years. At the end of the integration, 10 test particles were found on the orbits trapped in the Trojan region, suggesting a capture efficiency of $\sim$1%. The trapped Trojans all have eccentricities lower than 0.13. The more eccentric ones are lost, probably due to their closer distances to Uranus. The distribution of Trojan's inclinations is hardly affected. Although Uranus's eccentricity is somewhat stirred up and this influence needs further investigation, since the capture mechanism we proposed for 2005 TN_{53} still works with its existence.

However, the model in our numerical experiment is quite rough. We should carry out the process of Neptune's eccentricity damping and its relation with the rapid migration of Neptune in greater detail. All these aspects make it worth establishing a more realistic model in the future.

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