

Trailing (L_5) Neptune Trojans: 2004 KV18 and 2008 LC18 *

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Abstract The population of Neptune Trojans is believed to be bigger than that of Jupiter Trojans and that of asteroids in the main belt, although only eight members of this distant asteroid swarm have been observed up to now. Six leading Neptune Trojans around the Lagrange point L_4 discovered earlier have been studied in detail, but two trailing ones found recently around the L_5 point, 2004 KV18 and 2008 LC18, have not yet been investigated. We report our investigations on the dynamical behaviors of these two new Neptune Trojans. Our calculations show that the asteroid 2004 KV18 is a temporary Neptune Trojan. Most probably, it was captured into the trailing Trojan cloud no earlier than 2.03×10^5 yr ago, and it will not maintain this position later than 1.65×10^5 yr in the future. Based on the statistics from our orbital simulations, we argue that this object is more like a scattered Kuiper belt object. By contrast, the orbit of 2008 LC18 is much more stable. Among the clone orbits spreading within the orbital uncertainties, a considerable portion of clones may survive on the L_5 tadpole orbits for 4 Gyr. The strong dependence of the stability on the semimajor axis and resonant angle suggests that further observations are badly required to constrain the orbit in the stable region. We also discuss the implications of the existence and dynamics of these two trailing Trojans over the history of the solar system.

Key words: solar system: general — Kuiper belt — asteroids — methods: numerical

1 INTRODUCTION

The Trojans are celestial bodies moving on the same orbit as a planet, but around 60° ahead or 60° behind the planet close to the triangular Lagrange points L_4 (leading) or L_5 (trailing). By the original definition, only those asteroids on the so-called tadpole orbits are “real” Trojans (Murray & Dermott 1999). Jupiter is the first planet known to host thousands of this kind of asteroid after the discovery of (588) Achilles in 1906. Several Trojan asteroids around Mars were discovered quite recently in the 1990s (Bowell et al. 1990). Another ten years later, the first Neptune Trojan, 2001 QR322, was found to orbit around the L_4 Lagrange point (Chiang et al. 2003). In August 2011, the first Earth Trojan was confirmed (Mainzer et al. 2011) and its dynamics were studied very recently (Connors et al. 2011; Dvorak et al. 2012).

The Trojan asteroids are of special interest not only because their dynamics are complicated, but also because their origin and evolution may bear important clues to the early history of our solar system. Many studies, e.g. Nesvorný & Dones (2002); Marzari et al. (2003); Robutel & Gabern

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Table 1 Orbital elements of six L_4 Neptune Trojans, given at epoch 2012 March 14 with respect to the mean ecliptic and equinox at J2000. The semimajor axes are given in AU, while the angular elements, including inclination i , perihelion argument ω , ascending node Ω and mean anomaly M , are in degrees. All the data come from the website of IAU: Minor Planet Center with URL <http://www.minorplanetcenter.net/iau/lists/NeptuneTrojans.html>.

Designation	a	e	i	ω	Ω	M
2001 QR322	30.380	0.030	1.3	167.9	151.6	58.20
2004 UP10	30.302	0.032	1.4	2.2	34.8	345.02
2005 TN53	30.279	0.069	25.0	84.1	9.3	296.12
2005 TO74	30.282	0.053	5.2	299.7	169.4	278.22
2006 RJ103	30.195	0.029	8.2	16.8	120.9	256.40
2007 VL305	30.201	0.069	28.1	217.0	188.6	358.51

(2006); Robutel & Bodossian (2009); Dvorak et al. (2007, 2010); Zhou et al. (2009, 2011), have been devoted to the dynamics of Trojan asteroids near different planets. In recent years, the origin of Trojans and the formation of the Trojan cloud began to attract more attention (Morbideilli et al. 2005; Nesvorný & Vokrouhlický 2009; Lykawka et al. 2009, 2010) since the well-known “Nice Model” (for a review, see for example Crida 2009) about the early history of the solar system regards the existence and related properties of Jupiter Trojans as one piece of critical evidence of the theory (Morbideilli et al. 2005). In addition, although there are no observations of planets on Trojan-like orbits in an extra-solar planetary system to date, their potential existence and stability have also been investigated (see e.g. Dvorak et al. 2004; Ji et al. 2005, 2007; Goździewski & Konacki 2006).

Before the discovery of asteroid 2008 LC18 by Sheppard & Trujillo (2010a), six Neptune Trojans (NTs hereafter) have been observed. Their orbits are listed in Table 1. But they are all near the leading Lagrange point L_4 , about 60° ahead of Neptune. This is partly due to the fact that the trailing Lagrange point (L_5) is currently in the direction of the Galactic center. The background stars add difficulty to the discovery of asteroids in this “shining” region. As the first NT around the L_5 point, 2008 LC18 is of particular interest, not only because it is the first member of a possible asteroid swarm in which it resides, but also because a novel way has been used to block out the strong background light from the Galaxy’s center. Following this success, another L_5 NT (2004 KV18) was reported in July 2011 (Gladman et al. 2011), increasing the number of L_5 NTs to two. These two findings represent the first step to confirming the dynamical symmetry between the L_4 and L_5 points (Nesvorný & Dones 2002; Marzari et al. 2003; Zhou et al. 2009), and the high inclinations of their orbits (see Table 2) further add to the fraction of NTs on highly-inclined orbits (so far three out of a total of eight NTs have inclination larger than 25 degrees). Both of these two points give specific indications about the process of capturing NTs and the evolution of a planetary system in its early stage (Nesvorný & Vokrouhlický 2009; Lykawka et al. 2009, 2010). Meanwhile, the New Horizons¹ probe will travel through the area of space around Neptune’s L_5 point in a few years, thus the study of this region around L_5 is even more important than the one around L_4 .

It is difficult to explain the estimated 4:1 excess in inclination among the population of NTs (Sheppard & Trujillo 2006). Investigations on their dynamics show that the inclination of NTs is not likely to be excited *in situ* under the current planetary configuration. The only acceptable explanation seems to be that the NTs were captured rather than formed *in situ*, and the capture process pumped up the Trojans’ orbits, resulting in both high inclinations and high eccentricities (Nesvorný & Vokrouhlický 2009; Lykawka & Horner 2010). On the other hand, an NT orbit with an eccentricity larger than 0.1 seems to be unstable, thus the NTs excited in the early days of the solar system

¹ http://www.nasa.gov/mission_pages/newhorizons/main/index.html

Table 2 Orbital elements of asteroids 2008 LC18 and 2004 KV18, given at epoch JD=2455800.5 (2011-Aug-27) with respect to the mean ecliptic and equinox at J2000. The semimajor axes are in AU and the angular elements in degrees, as in Table 1. All elements and 1σ variations are taken from the AstDyS (see text). For the sake of comparing with our previous results, the orbital elements at epoch JD=2449200.5 (see text for explanation) are listed in columns indicated by “Val4Com.”

Element	2008 LC18			2004 KV18		
	Value	1σ	Val4Com	Value	1σ	Val4Com
a	29.9369	0.02588	30.1010	30.1260	0.01088	30.3927
e	0.083795	0.002654	0.080360	0.183846	0.000797	0.190021
i	27.5689	0.003824	27.5144	13.6092	0.001336	13.5684
Ω	88.521	0.0007854	88.549	235.6273	0.0004537	235.6852
ω	5.1349	10.85	8.9773	294.5615	0.1789	295.7312
M	173.909	12.83	130.057	58.5939	0.09	18.1013

should have been expelled from the Trojan cloud (Zhou et al. 2009, 2011). This is a puzzling aspect of the “capture origin” scenario.

Except for the newly found asteroid 2004 KV18, all other NTs have eccentricities below 0.1. Its highly eccentric orbit ($e = 0.184$, see Table 2) makes it so peculiar. Can this be the “smoking gun” to support the capture origin of the NT cloud, or is it not a remnant from the original dynamically excited Trojan cloud, but rather just passing by on its journey from the trans-Neptune region toward the inner part of the solar system? We take great interest to explore its dynamical properties to find some clues to the origin of these asteroids.

Last but not least, it is worth mentioning that the NTs represent a populated reservoir of small bodies (second only to the Kuiper belt), hosting about 400 objects larger than 50 km in radius, as estimated from the observation data by Sheppard & Trujillo (2010b). The main asteroid belt and the Jupiter Trojans, by comparison, contain about 200 and 50 objects of such size, respectively.

In this paper, we study in detail the dynamics of two L_5 NTs. The paper is organized as follows. We give our model and method of numerical simulation in Section 2. The simulation results are summarized and discussed in Section 3 for 2004 KV18, and in Section 4 for 2008 LC18. Finally, we make the conclusions in Section 5.

2 MODEL AND METHOD

The asteroids 2008 LC18 and 2004 KV18 have been observed at opposition two and three times respectively, and their orbits have been determined. The orbital elements, taken from the AstDyS (*Asteroids - Dynamic Site*) website², are listed in Table 2. The uncertainties, arising from the observation and orbital determination processes, are also listed in the Table. In our previous papers (Zhou et al. 2009, 2011), we have constructed dynamical maps and resonant maps on the (a, i) and (a, e) planes to show the locations of important resonances that govern the dynamics of NTs. If we find the positions of these two objects on the corresponding maps, we may immediately form a conjecture about their dynamical behaviors. For this sake, we transfer the orbital elements of these two objects to the epoch of JD=2449200.5 when the maps were composed. The corresponding orbital elements are also given in Table 2.

With the orbital elements of these objects, we perform numerical simulations to investigate their orbital evolutions and stabilities. We adopt the standard model of the outer solar system, namely a gravitational system consisting of the Sun and four Jovian planets from Jupiter to Neptune. The planets are in their current orbits and the NTs are assumed to be massless particles. Taking into

² <http://hamilton.dm.unipi.it>

account the uncertainties in the orbital elements, to make our investigations convincing, it is necessary to consider some clone orbits around the nominal orbits of these objects. Using the covariance matrix provided by the AstDyS, we generate a cloud of 1000 clone orbits for each object in the 6-dimensional space of orbital elements centered on the nominal orbit. The orbits are numerically simulated using the hybrid algorithm from the *Mercury6* package (Chambers 1999).

3 2004 KV18

For the asteroid 2004 KV18, 1000 clone orbits are integrated up to 10 Myr in both the forward (future) and backward (past) directions. The span of integration time (10 Myr) is chosen after some test computations, and it is long enough to show the behavior of the asteroid as being an L_5 NT. The location of the nominal orbit of 2004 KV18 on the dynamical map at epoch JD=2449200.5 (fig. 3 in Zhou et al. 2011), i.e. $(a, e) = (30.3927, 0.190021)$ as listed in Table 2, reveals that this orbit is located far away from the stable region. Thus this object must be on an unstable orbit. Note that we did not show the dynamical map at the section of the exact inclination 13.5684° , but we had the maps for $i = 10^\circ, 20^\circ$ in this paper and for $i = 15^\circ$, which is not presented in the paper, and the continuity helps us draw the above conclusion.

3.1 Lifespan as an L_5 Neptune Trojan

All the 1000 clones have quite irregular orbits in both integration directions. More than half of them gain semimajor axes larger than 100 AU by the end of integration (10 Myr), which makes them move far away from the NT region. Since our interests in this paper are mainly in terms of the fate of the asteroid as an NT, we track the variable σ defined as

$$\sigma = \lambda - \lambda_8,$$

where λ and λ_8 are the mean longitudes of the clone and Neptune, respectively. σ is the critical argument of the 1:1 mean motion resonance (MMR) between the clone and Neptune. For an L_5 Trojan, σ librates around -60° (or equivalently 300°). When the libration amplitude³ is relatively small, in the range $-180^\circ < \sigma < 0^\circ$, the Trojan is on a “tadpole orbit.” If the amplitude grows larger, to the range $\sigma < -180^\circ$, the asteroid may still stay in the 1:1 MMR but turn into a “horseshoe orbit.” Then, according to the original definition (Murray & Dermott 1999) it is no longer a “Trojan.” If σ circulates, the asteroid leaves the 1:1 MMR. In our simulations, we define the time t_1 , when for the first time σ goes beyond -180° , as the moment that a clone escapes from the Trojan cloud. When a clone begins to circulate for the first time at moment t_2 , it is regarded as having escaped from the 1:1 MMR.

In Figure 1, we summarize the distributions of t_1 and t_2 for the 1000 clones in both time directions. As judged by t_1 , none of the clones keep the L_5 NT identity within the timespan 10 Myr in both time directions. Moreover, all of the clones leave the 1:1 MMR in our simulations (although some of them were recaptured into the 1:1 resonance again by the end). This orbital instability is consistent with the conclusion drawn from locating the nominal orbit on the dynamical maps in our previous papers (Zhou et al. 2009, 2011).

By checking the data carefully, we find that the first escape from the Trojan orbit ($\sigma < -180^\circ$) in the forward integrations happens at ~ 46 kyr, and the escaping orbits quickly accumulate, forming the first peak at ~ 48 kyr. Soon afterwards, the highest peak appears around ~ 73 kyr. By ~ 165 kyr, 90% of the clones have left the L_5 region. For the backward integrations, the distribution of t_1 is more flat than that in the forward direction. The first escape happens at ~ -34 kyr, and the first peak appears here. Another peak emerges very quickly at ~ -58 kyr. About 30% of escapes occur

³ In this paper, the “amplitude” refers to the full range of σ variation, i.e. the difference between the maximal and minimal σ values.

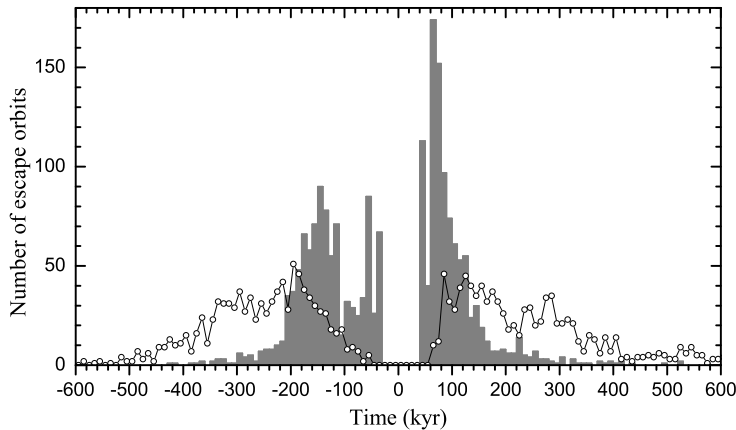


Fig. 1 Number of escape orbits per 10 kyr. The dark grey histogram in the background shows the distribution of t_1 when the clones leave the L_5 Trojan region (see text), while the curves with open circles represent the distribution of t_2 when the clone escapes from the 1:1 MMR.

in these two peaks. A wide peak centered at ~ -155 kyr contains nearly all the other clones. By -203 kyr, 90% of the clones have escaped from the L_5 tadpole orbits. Based on the above statistics, we may confidently conclude that the asteroid 2004 KV18 has been an L_5 NT for at least 34 kyr and it will keep this identity for at least 46 kyr in the future. But most probably, it is neither a primordial nor a permanent member of the L_5 NT cloud⁴. With a probability of 90%, it became an L_5 NT no earlier than 203 kyr ago and it will leave the L_5 region in less than 165 kyr.

Soon after leaving the tadpole orbits around the L_5 point, the clones escape the 1:1 MMR in both time directions, as shown by the t_2 distribution in Figure 1. In fact, after leaving the L_5 tadpole orbit and before it escapes from the MMR, a clone orbit may experience a horseshoe orbit, enter a tadpole orbit around the L_4 point, or even become a retrograde satellite of Neptune, but all these outcomes will only last for a very short time. We will show some details below.

3.2 Orbital Evolution

To show the temporal evolution of the clone orbits, in Figure 2 we plot the resonant angle (σ), semimajor axis (a), eccentricity (e), and inclination (i) of 50 clone orbits. These clones are selected arbitrarily (except for the nominal orbit) from the 1000 samples. Clearly the orbits are chaotic, as the orbits that are initially close to each other at time $t = 0$ become separated quite soon.

In the top panel, we see that the resonant angle σ librates for several periods in both the forward and backward directions before its libration amplitude increases beyond 180° where the clone enters the horseshoe orbit. The libration period T of a Trojan can be estimated through (see for example Murray & Dermott 1999)

$$T = 2\pi / \sqrt{\frac{27}{4}\mu},$$

where μ is the mass of Neptune with respect to the solar mass. This equation is only valid for tadpole orbits in the close vicinity of $L_{4,5}$ points, and it leads to a period of 8.9 kyr for NTs. But the 2004

⁴ By “primordial” we mean that the asteroid has been in the Trojan region since very early in the history of the solar system, before or just after the planets attained their current orbits, regardless of whether the asteroid was captured by or grew up with Neptune. By “permanent,” we mean that the asteroid will stay in the Trojan region until 4 Gyr in the future.

KV18 is quite far away from the L_5 point with a σ amplitude $\sim 100^\circ$ (see Fig. 2), and the libration period is ~ 10.7 kyr. A clone always leaves the L_5 region just after σ reaches the minimal value, and this explains the peaks that appear abruptly in Figure 1 at $t \sim -34$ kyr and $t \sim 48$ kyr. Between these two peaks, σ finishes seven whole libration periods. In addition, the libration amplitude must be tuned by some periodic effects (e.g. secular resonances), which is why some periodic features can be seen in the distributions of t_1 and t_2 in Figure 1.

After leaving the L_5 region in the future (or before being captured in the past), the clone may have different experiences before its final escape from the 1:1 MMR. It may librate with an amplitude larger than 180° , moving on a horseshoe orbit; it may shift to the tadpole orbit around the L_4 point and become a leading Trojan; or it may behave like a retrograde satellite around Neptune with σ librating around 0° with a small amplitude. The nominal orbit and another highlighted orbit in Figure 2 clearly show some of these possibilities. In a word, the asteroid 2004 KV18 is an L_5 NT right now, but it probably was and will be in the L_4 Trojan cloud, and it may change its identity several times while it is in the 1:1 MMR.

When a clone is on the tadpole orbit (either around the L_5 or L_4 point), its orbital evolution is more or less regular in this regime. For example, in the time ranging from -200 kyr to 70 kyr, the nominal orbit is an L_5 Trojan orbit as indicated by σ 's behavior, and we find its semimajor axis, eccentricity and inclination all behave regularly, as shown in Figure 2. For another highlighted orbit (blue curves in Fig. 2), the tadpole stage is from -150 kyr to 140 kyr (L_5 first and L_4 later, shifting at ~ 70 kyr); again the regular evolutions in a , e and i can be clearly recognized.

The regular motion must be a transient phenomenon, because the orbit is located on the separatrix of the 1:1 MMR. This region is characterized by strong chaos induced by overlaps of the secondary resonances (see for example Michtchenko & Ferraz-Mello 1995). Moreover, comparing the orbital elements with the resonance map in our previous papers (Zhou et al. 2009, 2011), we see that 2004 KV18 may be strongly influenced by a combined resonance characterized by $2f_\sigma - f_{2:1} + g_6 = 0$, where f_σ and $f_{2:1}$ are the frequencies of the resonant angle σ and the quasi 2:1 MMR between Neptune and Uranus, and g_6 is the apsidal precession rate of Saturn.

As soon as the clone leaves the 1:1 MMR, the orbital evolution will be very chaotic. This chaos arises from the overlap of first-order MMRs in the close vicinity of a planet's orbit (Wisdom 1980; Duncan et al. 1989). In addition, because Neptune and Uranus are very close to the 2:1 MMR, some clones will enter the 2:1 MMR with Uranus immediately after it escapes the 1:1 MMR with Neptune. In fact, the nominal orbit is in the 2:1 MMR with Uranus from 70 kyr to 170 kyr when its a librates around 30.7 AU with a small amplitude, as shown in the second panel of Figure 2.

Due to the strong chaos, it is hard to precisely predict the long-term fate of the clones after they escape from the 1:1 MMR, or inversely in time, to trace their origins back before being captured into this 1:1 MMR. However, we can still summarize some informative statistics on their evolutions as follows.

3.3 Past and Future

Based on the behaviors of the semimajor axis a and resonant angle σ , we divide the clone orbits into seven categories:

- Tadpole orbits (TDs)
- Horseshoe orbits (HSs)
- Retrograde satellite (RSs)
- Centaurs (CTs)
- Transneptunian objects⁵ (TNOs)

⁵ Roughly speaking, Transneptunian Objects (also known as the ‘‘Kuiper belt objects’’) are those celestial objects whose semimajor axes are larger than that of Neptune; Centaurs are celestial objects with semimajor axes between those of Jupiter and Neptune.

- Passing by orbits (PBs)
- Ejected objects (EJs)

Actually, the first three are all classified as co-orbital motions. They have similar a , but differ from each other by the libration center of σ : $\pm 60^\circ$ for TD, $\pm 180^\circ$ for HS, and 0° for RS. As for Centaurs and TNOs, our definition is not so rigid. For a clone whose σ does not librate, we simply check if its semimajor axis is larger or smaller than the upper or lower boundary of a Trojan's semimajor axis. This boundary is estimated through $\frac{d}{D} \approx \sqrt{3\mu} a_8$ where d and D represent the amplitudes of a and σ , respectively, and a_8 is the semimajor axis of Neptune. Here the angular boundary D is set to be 70° according to our previous study (Zhou et al. 2009), and the upper and lower boundaries of a are then defined by $a_8 \pm d$. The orbits located beyond the upper boundary are regarded as TNOs, while CTs are those inside the lower boundary. If, in a watch window, the semimajor axis of a clone excurses both sides of the Trojan boundaries, it is assigned to the PB category. Finally, those with a semimajor axis larger than 100 AU are regarded as being ejected from the system. We set the width of a watch window to be 50 kyr, covering about five full libration periods of a tadpole orbit. Over the duration of 10 Myr for our simulations, ten evenly distributed windows are set. We check the 1000 clones in every window and the statistical results are illustrated in Figure 3.

The forward and backward integrations give more or less the same results in Figure 3. Note that though we find RSs when closely examining the orbits, no RS appears in Figure 3. Generally the RS phase for a clone orbit lasts only for a very short duration, and it cannot be recognized by our numerical categorization code. On one hand, we need a longer window width to derive the type of orbit; on the other hand, we need a shorter time interval to avoid type mixing in a window. Surely such a dilemma also causes deviations to other categories, but not too much.

As Figure 3 shows, the number of PBs and all co-orbital cases (TD and HS) decreases with time, indicating that these orbital types are only temporary phases, and not likely to be the final destiny of 2004 KV18. Also, the portion of TNOs and CTs seems to not change much after 3×10^5 yr, implying that they may be the final outcomes for 2004 KV18. Since the number of CTs is smaller than that of TNOs, and this number decreases slightly with time, we argue that it is more probable that 2004 KV18 was always a TNO and will continue to be one rather than being a Centaur.

4 2008 LC18

At first glance, the asteroid 2008 LC18 is more like a typical NT than 2004 KV18, because it has a small eccentricity. Locating the nominal orbit (a, e, i) at epoch JD=2449200.5 on the dynamical maps in our previous papers (figure 3 in Zhou et al. 2011), we know that it is on the edge of a stable region. Its *spectral number*⁶ (SN) is ~ 50 . This SN is nearly the same as the ones for the L_4 NTs, 2005 TO74 and 2001 QR322, but is larger than the SNs for four other L_4 NTs, so the stability of 2008 LC18 is comparable to 2005 TO74 and 2001 QR322, whose orbits have been discussed before (Brasser et al. 2004; Li et al. 2007; Horner & Lykawka 2010; Zhou et al. 2011). In fact, in the paper reporting the detection of 2008 LC18, Sheppard & Trujillo (2010a) mentioned that all the orbits of known NTs at that time (seven NTs except for 2004 KV18) “are stable for the age of the solar system.” By contrast, 2004 KV18, discussed in the previous section, has an SN > 100 , indicating a very chaotic and thus unstable orbit.

The orbit of 2008 LC18 is less precisely determined compared to 2004 KV18, as indicated by larger 1σ variations in Table 2. Using the same method for 2004 KV18, a cloud of 1000 clone orbits is generated around the nominal orbit in the 6-dimensional space of orbital elements. The initial conditions $(a, e, i$ and $\sigma)$ of these clones can be seen in Figure 4. We integrate these clone orbits for

⁶ The spectral number indicates the regularity (or stability) of an orbit. A regular (thus stable) orbit has a small SN while a chaotic (unstable) orbit has a large SN. See for example Michtchenko & Ferraz-Mello (2001) for a definition.

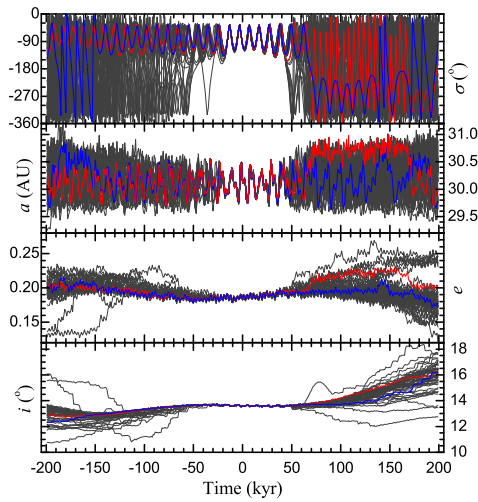


Fig. 2 From top to bottom, we show the temporal evolution of the resonant angle (σ), semimajor axis (a), eccentricity (e) and inclination (i) of 50 clones. The nominal orbit is represented by the thick, red curves. Another arbitrarily selected orbit is highlighted and plotted in blue (see text).

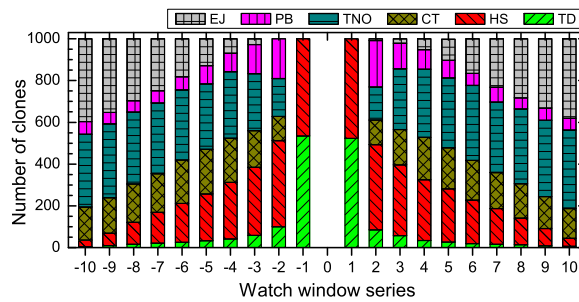


Fig. 3 States of the 1000 clones in ten watch windows (50 kyr each) evenly spread over the 10 Myr duration of both the forward and backward integrations. The series of numbers in the windows are in a temporal sequence.

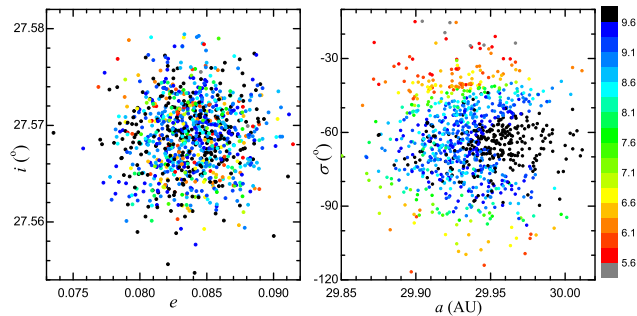


Fig. 4 The initial conditions of clone orbits of 2008 LC18. The color code indicates the lifetime of the clone as an L_5 NT (given as t_1 in Fig. 1, on a logarithmic scale). Those orbits staying on the L_5 Trojan orbits for the whole timespan of the simulation (4 Gyr) are indicated by black dots.

4×10^9 yr (4 Gyr, roughly the lifetime of the solar system) in both forward and backward directions. The results are presented below.

4.1 Initial Conditions and Orbital Stability

We monitor the resonant angle σ of each clone orbit in the numerical simulations. When $\sigma < -180^\circ$ for the first time (t_1), the identity of the clone as an L_5 NT is regarded as ending. In our calculations, we found that as soon as a clone deviates from the tadpole orbit, it will leave the 1:1 MMR shortly afterwards. Therefore, we ignore the moment of escape from the 1:1 MMR, i.e. t_2 , and only focus on t_1 in this part.

Among the 1000 clones, for both forward and backward integrations, the first escape from the L_5 Trojan region happens at 2×10^5 yr, but most clones survive in the L_5 cloud beyond 10^8 yr. In Figure 4 we show the dependence of the lifetimes (t_1) of clone orbits on the initial conditions. Since our calculations reveal a good temporal symmetry, i.e. the results from the backward integrations are nearly the same as the results from the forward integrations (this can also be seen clearly in Fig. 5), we only show the case for the forward integration in Figure 4.

All points with different colors, including the black points indicating the most stable orbits surviving 4 Gyr on the Trojan orbits, are spread uniformly in the (e, i) cloud of initial conditions in the left panel of Figure 4. This uniform distribution indicates that within the range of uncertainty for the orbital elements, the lifetime (t_1) has no relation with either the initial eccentricity e or the initial inclination i . We also carefully check the dependence of lifetime on the initial angular variables (ω, Ω, M) and find that the stability does not have apparent relevance to these angular orbital elements either (within the error ranges, of course). Nevertheless, the stability depends on the summation of ω, Ω and M , namely the mean longitude $\lambda = \omega + \Omega + M$. More precisely, it depends on the resonant angle $\sigma = \lambda - \lambda_8$, as shown in the right panel of Figure 4.

Also in this picture, the dependence on the semimajor axis is apparent. The color points make a layered structure. The most unstable orbits occupy the outer layer to the left, and we find that both too large ($\sigma > -40^\circ$) and too small ($\sigma < -100^\circ$) initial σ leads to unstable motion. Meanwhile, nearly all the most stable orbits are concentrated in the inner layer to the right. The gathered black points form a triangle in the region of middle σ ($\sim -65^\circ$) and large a (> 29.93 AU), and no color points exist in this triangle.

The libration amplitude of σ is in fact related to the initial semimajor axis. The further the initial a is from the resonant center, the larger the amplitude of σ is. Thus, the layered structure in the right panel may be equivalent to the vertical stripe structure in the dynamical maps on the (a, e) plane in our previous paper (Zhou et al. 2011), where the initial σ is fixed. The ‘‘C type’’ secular resonances defined in the same paper were found to be responsible for the vertical structures. Recalling the position of 2008 LC18 on the (a, e) and (a, i) planes, we find that the layered structure on the (a, σ) plane in Figure 4 is probably due to one of the ‘‘C type’’ resonances: $4f_\sigma - 2f_{2:1} + g_6 + g_7 = 0$.

The probability of finding NTs in the stable region should be much higher than in the unstable region, thus 2008 LC18 is expected to be on a stable orbit. We would argue that further observations in the future will constrain its orbit to the stable region, in particular, the semimajor axis and the corresponding resonant angle to the triangle on the (a, σ) plane in Figure 4, as we mentioned above.

Starting from the 1000 clones and after 4 Gyr of orbital evolution, there are still 262 clones surviving in the L_5 region ($t_1 > 4$ Gyr) in the forward integration. As for the backward integration, 252 orbits survive. In a word, more than 25% of clones stay on the tadpole orbit around the L_5 point for 4 Gyr in both forward and backward directions. The clones escape from the L_5 region over a wide span of time beginning from 2×10^5 yr. The number of clones that survive on the tadpole orbits decreases with time. In Figure 5, we plot such decline in the number of clones for integrations in both directions.

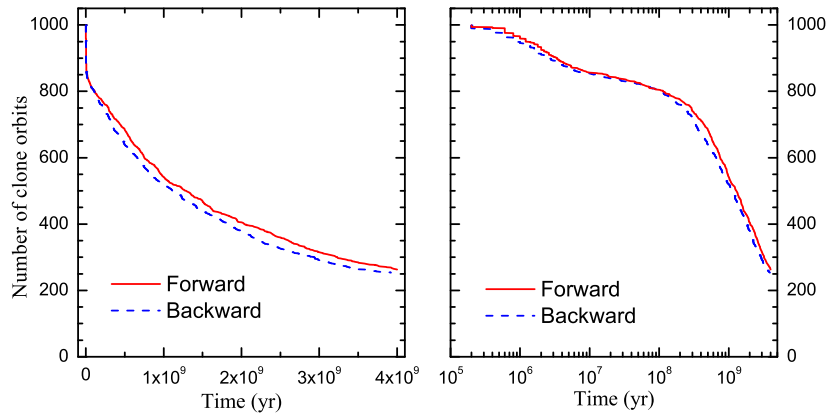


Fig. 5 The number of clones that survive in the L_5 cloud decreases with respect to time. In the *left panel* the time is on a linear scale while in the *right panel* it is on a logarithmic scale. The solid curves are for the forward integrations, and the dashed curves are for the backward integrations.

Two curves for the forward and backward integrations in Figure 5 coincide with each other, implying the nearly exact symmetry between two temporal directions. From the profiles of these curves, two stages of the escape process, which intersect each other at $\sim 10^7$ yr, can be clearly recognized. In the first stage, about 15% of clones (~ 150 clones) quickly escape from the L_5 region, while in the second stage, the number of surviving clones slowly decreases. As indicated by the escape times (color) in Figure 4, nearly all the clones that escape in the first stage have initial resonant angles of either $\sigma_0 > -40^\circ$ or $\sigma_0 < -100^\circ$. The clones escaping in the second stage on the other hand have $-40^\circ < \sigma_0 < -100^\circ$.

In fact, the dynamical studies have shown that the stable region is separated from the unstable region by a sharp edge, i.e. the intermediate area is very narrow (Zhou et al. 2011). Thus it is natural to see that those orbits initially located in the unstable region quickly escape, causing a rapid decrease in the first stage in Figure 5, while those orbits in the stable region escape slowly in the second stage. We believe that 2008 LC18 is a typical NT rather than a temporary NT like 2004 KV18. Further observations will reduce the uncertainties of the orbit and probably exclude those unstable clone orbits that escape in the first stage. Then the decay in the second stage will give the “proper” survival probability for this kind of object in the L_5 region.

Moreover, for those orbits initially in the stable region, their orbital elements may diffuse very slowly on the dynamical map and the instability can set in “abruptly” when the orbit crosses the narrow transitional area. Such an example of a sudden escape from the L_5 region is shown in the following section.

4.2 Orbital Evolution

We have shown in the above section the ensemble behavior of clone orbits, and we will now turn to the evolution of individual orbits. But in fact, the orbital evolution of clones of 2008 LC18 is relatively plain. As an example, we illustrate the temporal evolution of the nominal orbit of 2008 LC18 in Figure 6.

From the behavior of resonant angle σ in the top panel of Figure 6, the nominal orbit was captured to the L_5 tadpole orbit about 1.678 Gyr ago, and it will leave the L_5 Trojan region in about 3.505 Gyr. During its time as an L_5 Trojan, the semimajor axis, eccentricity and inclination behave

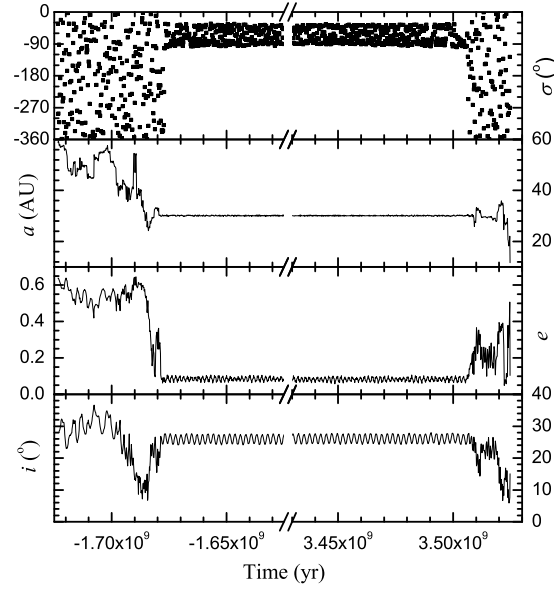


Fig. 6 Temporal evolution of the resonant angle (σ), semimajor axis (a), eccentricity (e) and inclination (i) of the nominal orbit of 2008 LC18. Note the break in the abscissa axis.

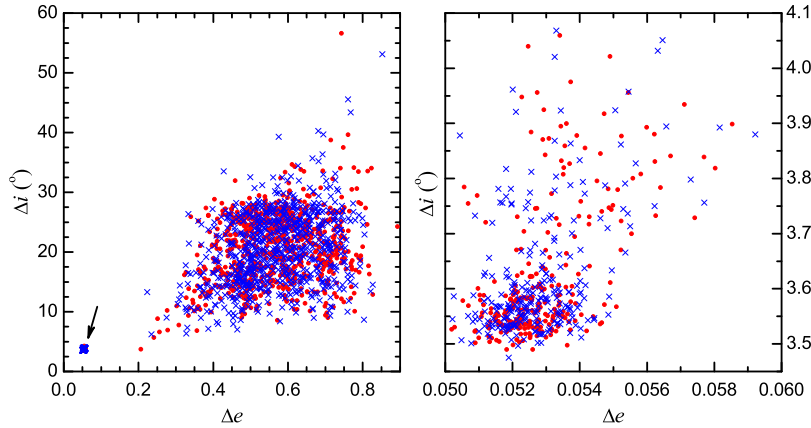


Fig. 7 The variations of the eccentricity and inclination of clone orbits. The red solid circles are for the forward integrations and the blue crosses for backward integrations (*color online*). The right panel shows the variations for those stable orbits surviving in the L_5 region for 4 Gyr. It is an enlargement of the lower left corner of the left panel, indicated by an arrow (see text).

very regularly, varying with small amplitudes. In particular, the amplitude of σ is smaller than 40° during most time of its life. No apparent secular variations of a , e , i or σ can be observed in the time range when it is on the tadpole orbit as a Trojan. As mentioned above, the chaos seems to set in suddenly. This is due to the fact that the border between the stable and unstable region is narrow, and a small deviation from the stable region may result in the destruction of its stability.

Actually, all those stable orbits that survive on the tadpole orbits in both time directions for 4 Gyr behave in a similarly regular way as the nominal orbit in the Trojan phase from -1.678 Gyr to 3.505 Gyr. Their semimajor axes oscillate between 29.98 AU and 30.4 AU, their eccentricities are always smaller than 0.12 , their resonant angles librate around -60° with amplitudes $\sim 30^\circ$, and their inclinations librate around 26° with amplitudes smaller than 4° . In spite of their high inclination, no apparent nodal secular resonance is observed.

The second panel of Figure 6 shows that the semimajor axis of the nominal orbit was beyond the orbit of Neptune before it was captured into the Trojan cloud, and it will be inside Neptune's orbit after it leaves the L_5 region. Therefore, it had become an NT from a scattered TNO and it will finally become a member of the Centaurs in the future. However, it is worth noting that we may draw conclusions from our calculations about the destiny of these clones 4 Gyr into the future, but no solid conclusions can be made about their origins 4 Gyr ago in the past. The solar system is currently quite "clean," but 4 Gyr ago the orbits of planets had probably not settled down and the planetesimal disk or even the gas disk still existed. Even if the computational error (roundoff error and model error) could ideally be controlled to infinite precision and thus ignored, the origin of an NT cannot be determined by tracing its orbit back through backward integration, because the exact circumstances at that time are far from being understood.

4.3 Inclination Excited *in situ*?

Although the eccentricity of 2008 LC18 is small (~ 0.08), its inclination is quite high ($\sim 27.5^\circ$), suggesting it is a typical excited orbit. The high inclination of some NTs is an important puzzle and perhaps also a key clue for the understanding of their origins and orbital evolutions. Based on our calculations for those 1000 clones, we discuss the excitation of NT orbits in this section, particularly, we will check the possibility of inclination being pumped up *in situ*.

The dynamical studies reveal that numerous secular resonances are involved in the orbital dynamics of NTs, even in the stable region of the space of orbital element (Zhou et al. 2009, 2011). The effects of these resonances may not be strong enough for the orbital stability of NTs to be destroyed in the age of the solar system. But they may drive the orbits of NTs to diffuse slowly in the element space, so that a primordial NT may attain a high inclination through this slow diffusion. To clarify whether this process is responsible for the inclination of 2008 LC18, we examine the variations in eccentricity Δe and inclination Δi of clone orbits during the simulations. Here Δe and Δi are the full ranges of varying eccentricity and inclination, defined as the differences between the maximal and minimal values of e and i in the entire simulation. The results are summarized in Figure 7.

In the left panel of Figure 7, clone orbits are divided into two separate groups. One group extends from $\Delta e = 0.2$ to $\Delta e = 0.85$, and the other one is confined in a small area at low Δe and low Δi , indicated by the arrow in the plot. We pick out all the stable orbits surviving 4 Gyr in our simulations in both directions of integration and plot their variations of e and i in the right panel of Figure 7. Apparently, the above mentioned group of orbits located in the lower left corner of the left panel consists of only those stable orbits. All the stable orbits have small variations in eccentricity and inclination, i.e. $0.05 < \Delta e < 0.06$ and $3.45^\circ < \Delta i < 4.10^\circ$. For those stable orbits, the inclination neither decreases significantly in the backward integration nor increases in the forward integration. Hence the inclination of 2008 LC18 seemingly has not risen under the current configuration of the solar system.

However, those unstable orbits occupy the lower right half of the left panel in Figure 7, reflecting that most of them experience large variations in eccentricity. A careful examination of the orbits reveals that the variation in eccentricity is caused either by crossing through MMRs (between clones and planets) or by close encounters of the clones with planets. Both of these two mechanisms work only when the clones are outside the Trojan phase. The increased eccentricity for a clone will generally result in further close encounters with planets. These encounters cause large variation in

inclination. That is the reason why a large variation in inclination is always accompanied by a large variation in eccentricity. By contrast, the lack of orbits in the upper left region of the picture clearly shows that no excitation in inclination could happen without the excitation in eccentricity.

Regarding the question of whether the inclination of 2008 LC18 can be excited *in situ*, our calculations give a negative answer. But our calculations suggest that during the process of capturing asteroids into the Trojan orbits, their inclinations might be pumped up, mainly through close encounters with planets. After the capture, there must be some braking mechanisms that can dampen the eccentricity but preserve the inclination.

5 CONCLUSIONS

The Trojan cloud around the triangular Lagrange points L_4 and L_5 of Neptune is believed to be a large reservoir of asteroids, hosting more asteroids than Jupiter's Trojan cloud or even the main asteroid belt between Mars and Jupiter (Sheppard & Trujillo 2006, 2010b). Up to now, six leading NTs around the L_4 point and two trailing ones around the L_5 point have been discovered. The dynamics of the L_4 NTs have been studied by several authors (e.g. Marzari et al. 2003; Brasser et al. 2004; Li et al. 2007; Horner & Lykawka 2010). In this paper, taking into account the errors introduced in the observations and orbital determinations, we investigate the orbital dynamics of two trailing NTs, 2004 KV18 and 2008 LC18⁷. Starting from clouds of clone orbits around the nominal orbits, we simulate the clones' orbital evolutions using the well-known *Mercury6* numerical integrator package.

Our results suggest that 2004 KV18 is on an especially unstable orbit. It is neither a primordial nor a permanent NT, but rather a passing object on its way between being a TNO and a Centaur. Its lifetime as a trailing NT is on the order of 10^5 years in the future, and probably it has been on such an unstable tadpole orbit for less than 2×10^5 years. Such an unstable orbit means that it can neither be regarded as the smoking gun of "the hot Trojan" from the chaotic capture model (Nesvorný & Vokrouhlický 2009) nor as a case from the migrating Neptune model (Lykawka et al. 2009, 2010; Lykawka & Horner 2010).

Due to the orbits being highly chaotic, it is hard to draw a solid conclusion about where the asteroid came from or where it will go in the long term. But statistics on the clone orbits still give some helpful information, suggesting that most probably it will evolve to be a TNO after leaving the L_5 region.

The asteroid 2008 LC18 however is more like a primordial trailing NT. Our calculations show that an appreciable proportion of clone orbits within the limits of orbital errors survives on the tadpole orbits for 4 Gyr and their orbital evolutions are very regular in both forward and backward directions of time. In particular, the high inclination of the orbit does not change much, implying that the orbit has not been excited on the tadpole orbit under the current planetary configuration. On the contrary, for those clone orbits escaping from the tadpole orbit, their inclinations may vary significantly when they are outside of the Trojan phase. These calculations imply that 2008 LC18 may have been captured onto the current highly inclined orbit very long ago, and during the capturing process its inclination may be excited due to close encounters with planets.

The orbital stability of clones of 2008 LC18 apparently depends on the semimajor axis and the resonant angle. Nearly all the stable orbits are in a specific region of the (a, σ) plane, so we expect that additional observations will constrain the orbit in this region.

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⁷ During the publishing process of this paper, we were reminded by Dr. Horner that they have an accepted paper (Horner et al. 2012), in which the orbit of 2008 LC18 was discussed.

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