

Formation of the Kuiper Belt by Long Time-Scale Migration of Jovian Planets *

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Abstract The orbital migration of Jovian planets is believed to have played an important role in shaping the Kuiper Belt. We investigate the effects of the long time-scale (2×10^7 yr) migration of Jovian planets on the orbital evolution of massless test particles that are initially located beyond 28 AU. Because of the slowness of the migration, Neptune's mean motion resonances capture test particles very efficiently. Taking into account the stochastic behavior during the planetary migration and for proper parameter values, the resulting concentration of objects in the 3:2 resonance is prominent, while very few objects enter the 2:1 resonance, thus matching the observed Kuiper Belt objects very well. We also find that such a long time-scale migration is favorable for exciting the inclinations of the test particles, because it makes the secular resonance possible to operate during the migration. Our analyses show that the ν_8 secular resonance excites the eccentricities of some test particles, so decreasing their perihelion distances, leading to close encounters with Neptune, which can then pump the inclinations up to 20° .

Key words: celestial mechanics — Kuiper Belt — methods: numerical — solar system: formation

1 INTRODUCTION

The Kuiper Belt (KB hereafter) is a disk of small icy objects that orbit the Sun beyond Neptune. With the discovery of the first member of the Kuiper Belt Objects (KBOs hereafter), 1992QB1 (Jewitt & Luu 1993), the KB was transformed from a theoretical conjecture (Edgeworth 1943; Kuiper 1951) to a bona fide component of the Solar system. At the time of writing, more than 1000 KBOs have been discovered. Since these objects are thought to be the remnants after the planets had accreted most of their masses, they may provide us with many clues to the formation and primordial evolution of the outer Solar system.

The observed KBOs¹ can be grouped into one of three dynamical classes according to their orbital characteristics (e.g. Luu & Jewitt 2002; Elliot et al. 2005): (1) Classical KBOs. They represent about two-thirds of the observed KBOs, mostly with semimajor axes $42 \text{ AU} < a < 48 \text{ AU}$, having typically small to moderate eccentricities and inclinations. However, recent observations show that a 'hot' population with inclinations larger than 30° reside in this classical region. (2) Resonant KBOs. These are trapped in the mean motion resonances (MMRs) with Neptune,² and have moderate to large eccentricities ($0.05 < e < 0.3$). They account for about 25% of the observed sample. Most of them share Neptune's 3:2 MMR ($a \approx 39.4 \text{ AU}$) with Pluto (so they are called 'plutinos'), and the few remaining ones reside in the 4:3, 5:3 and 2:1 resonances. Besides, there are the Neptune Trojans³ (four have been discovered) located at the 1:1 resonance with Neptune and having the same period as Neptune (Chiang & Lithwick 2005). (3) Scattered KBOs, moving in elliptic orbits with perihelia beyond Neptune. Their eccentricities range from 0.2 to 0.85

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¹ <http://cfa-www.harvard.edu/cfa/ps/lists/TNOs.html>

² i.e., when the ratio of the orbital periods of the KBO and Neptune can be expressed by two small integers.

³ which librate about one of Neptune's triangular Lagrange points.

with inclinations less than 40° . They comprise about 8% of the observed objects. How the KB evolved to the current configuration is a key problem of the early evolution of the Solar system. Although it is out of the scope of this paper, we shall address the strikingly high frequency of binaries in KBOs, an estimated fraction of 10% to 20% (e.g. Sheppard & Jewitt 2004).

Planetary migration and the mechanism of resonance sweeping shed light on the structure of the KB. The numerical simulations undertaken by Fernández & Ip (1984) showed that Jovian planets had experienced orbital migrations due to exchange of energy and angular momentum between the planets and the remnant planetesimal disk in the primordial Solar system. Malhotra (1993, 1995) developed the resonance sweeping mechanism. She introduced an artificial ‘drag’ force on the planet to drive its smooth radial migration. As Neptune migrated outwards, its MMRs swept through the original KB and many small objects were captured and locked in these resonances (primarily the 3:2 and 2:1 resonances). Malhotra’s pioneering planetary migration/resonance sweeping theory has successfully explained the depletion of objects interior to Pluto’s orbit, the significant population of plutinos (in the 3:2 resonance), and plutinos’ high eccentricities. However, her prediction of a concentration of objects in the 2:1 resonance does not agree with the observed fact that not many objects are observed there.

In reality, the planetary migration is not smooth. Due to the random encounters between planets and planetesimals, the migration is a stochastic process with only a mean trend. Such ‘to-and-fro’ phenomena were observed in the numerical simulations (Fernández & Ip 1984; Hahn & Malhotra 1999). Zhou et al. (2002) modelled the stochastic effects in the migration. Their model does quite a good job at decreasing the concentration at the 2:1 resonance while holding a large population at the 3:2 resonance. Consequently, resulting in an orbital distribution that matches the observational data much better. A migration time-scale $\tau = 2 \times 10^6$ yr was adopted in their model, but the numerical simulations of Fernández & Ip (1984) and Hahn & Malhotra (1999) show that a ‘realistic’ time-scale should be $\mathcal{O}(10^7)$ yr. Moreover, a slower migration is found to be more efficient in capturing objects into the 2:1 resonance (Ida et al. 2000b), thus weakening the effect of stochastic migration on decreasing the relative population in the 2:1 resonance. In Zhou et al. (2002), the inclinations of KBOs are not excited enough in comparison with the observed sample, while a possible correlation between higher inclinations and larger τ is suggested by Malhotra (1995). As we shall show, a possible new mechanism, which cannot occur in a fast migration, may increase the inclinations of KBOs. All these make it worthwhile to carefully examine the case of long time-scale evolution.

In this paper we numerically simulate the orbital evolution of a large number of test particles under such a long time-scale, stochastic planetary migration. The rest of this paper is organized as follows. In Section 2, we briefly present the scenario of migrations of Jovian planets and describe our model. In Section 3 we give our numerical results, compare the discrepancies of the KB structure between the long time-scale ($\tau = 2 \times 10^7$ yr) case and the shorter one ($\tau = 2 \times 10^6$ yr), and analyze the origin of the high-inclination test particles. Our conclusions are given in Section 4 together with a discussion.

2 MODEL

In the late stages of the Solar system formation, the four giant planets had reached their present sizes and were moving on well-separated, nearly-circular and coplanar orbits. The solar nebula was depleted already, but there remained a residual planetesimal disk. Gravitational scattering and accretion of the small bodies modified the orbits of the planets.

If there was only Neptune, there would be approximately equal numbers of inward and outward scattering planetesimals. Neptune conserves its angular momentum and no net change of its orbital radius happens. However, the symmetry is broken if the four Jovian planets work together (Fernández & Ip 1984). The objects scattered outwards escape from the planetary system, enter the far-flung Oort Cloud or return to be rescattered. Consider those scattered inwards where the inner Jovian planets, particularly Jupiter, control the dynamics. The massive Jupiter is very effective in scattering objects into escape orbits of the Solar system, some of these planetesimals encounter Neptune again. As a result, some angular momentum and energy are transferred from Jupiter to Neptune and the latter migrates outwards. Fernández & Ip (1984) showed that Neptune, Uranus and Saturn gain orbital angular momentum and migrate outwards while Jupiter, as the ultimate source of the angular momentum and energy, moves sunward.

On the other hand, in order to check the effects of the planetary migration on the formation of the KB, Malhotra (1993, 1995) assumed a time variation of the orbital semimajor axes of the Jovian planets of the

form,

$$a(t) = a_f - \Delta a \exp(-t/\tau), \quad (1)$$

where a_f is the current semimajor axis, $a(t)$ is the semimajor axis at epoch t , and τ is the migration time-scale; Δa is the amplitude of migration, which is assumed to be 7.0 AU for Neptune and $-0.2, 0.8, 3.0$ AU respectively for Jupiter, Saturn, Uranus (Malhotra 1993, 1995; Zhou et al. 2002). We noticed that the numerical simulations of the migration process, both by Fernández & Ip (1984) and Hahn & Malhotra (1999), gave a migration time-scale of $\mathcal{O}(10^7)$ yr, so we set $\tau = 2 \times 10^7$ yr.

The Solar system in our numerical simulations consists of the Sun with the masses of four terrestrial planets added, and the four Jovian planets. We model the orbital migration as in Zhou et al. (2002) by adding an artificial, random force on each planet along the direction of the orbital velocity \hat{v} , as:

$$\Delta \ddot{\mathbf{r}} = \frac{\hat{v}}{\tau} \left\{ \sqrt{\frac{GM_\odot}{a_i}} - \sqrt{\frac{GM_\odot}{a_f}} \right\} (1 + \beta S_n) \exp\left(-\frac{t}{\tau}\right), \quad (2)$$

where $a_i = a_f - \Delta a$ is the semimajor axis at the starting pointing ($t = 0$). The planets' orbital elements are taken from the JPL's WWW site⁴ and their masses are taken from DE405 (Standish 1998). In Equation (2), S_n is a Gaussian random variable with zero mean and standard deviation $\sigma = 0.2$. The subscript in S_n is determined by $n = \text{Int}[t/T]$ with T a pre-selected sampling interval. We use β to control the amplitude of variability. When $\beta = 0$ the force in Equation (2) will derive a migration as described in Equation (1).

Here we just explore the effects of the long time-scale planetary migration, with different magnitudes of the stochastic effects, on the formation of the KB. We simply fix T at 30 000 yr. Roughly, a smaller T means a more frequent gravitational scattering between the planets and the planetesimals.

We numerically simulate the evolution for different values of β . In each run of simulation, there are 200 test particles (representing the KBOs) with initial semimajor axes distributed uniformly in the range 28–47.9 AU. For each β , we make two simulation runs, one a thin disk (in which the initial eccentricities e and initial inclinations i of test particles are set at 0.01) and one for a thick disk (initial $e = i = 0.05$). All the other angles of the orbit (longitude of perihelion ϖ , longitude of ascending node Ω , and mean longitude λ) are chosen randomly in the range 0 – 2π .

An orbital integrator based on the second-order symplectic map (Wisdom & Holman 1991) is used. The scheme has been constructed after Mikkola (1998) and Mikkola & Palmer (2000), and can deal with non-canonical perturbations such as drag force. We integrate the system for 2×10^8 yr that is 10 times the assumed orbital migration time-scale, τ . We set the step at 200 d, about one-twentieth of the Jupiter's sidereal orbit period.

In each run, we choose appropriate parameters to ensure that the final state resembles the present configuration of the outer solar system. The final semimajor axes, eccentricities and inclinations of the four Jovian planets fit the current observed data very well. For the profile of the temporal evolution of Neptune's semimajor axis, see figure 1 of Zhou et al. (2002).

In our numerical simulations, we discard any test particles that have suffered close approaches, i.e., within one Hill sphere radius, with any one of the Jovian planets. Zhou et al. (2002) calculated the Lyapunov time T_e of each test particle and used it to judge whether an orbit is stable enough to survive long enough to be included in the final statistics (the threshold is $T_e = 10^5$ yr). In fact we have calculated T_e of the "confirmed" KBOs⁵ and found a few amazingly small values ($\leq 10^3$ yr). Thus in this paper we will not use T_e to judge the survivability. Our final statistics include all objects that did not come within one Hill sphere radius of any of the planets over the integration time.

3 RESULTS

Our numerical simulations reproduce some similar results to the previous work (Zhou et al. 2002), indicating that under the long time-scale migration with the stochastic effects the resonance sweeping mechanism can still account for the formation of the KB's structure. In addition, the long time-scale simulation has brought out some noteworthy new features.

⁴ http://ssd.jpl.nasa.gov/elem_planets.html

⁵ KBOs that have been observed at two oppositions or more.

3.1 Final Orbits of the Test Particles

As mentioned above, we numerically simulate the orbital evolution of a large number of test particles. Figures 1 and 2 summarize the final distributions of their semimajor axes, eccentricities and inclinations after 2×10^8 years of integration for different values of β . For clarity, the final orbital elements a , e and i have been averaged over the last two million years in the integrations.

Figures 1 and 2 reproduce some similar features as in the previous work (Zhou et al. 2002) calculated for a planetary migration time-scale of $\tau = 2 \times 10^6$ yr and an integration time of 3×10^7 yr: (1) The region between 28–36 AU is nearly unoccupied; (2) The population is highly concentrated in two MMRs with Neptune – the 3:2 and 2:1 resonances, located near 39.4 and 47.7 AU, respectively; other resonances, such as the 4:3 (36.4 AU) and 5:3 (42.3 AU) resonances, also contain a few objects; (3) As β increases, the concentration in the 3:2 resonance is well kept up while fewer and fewer objects enter the 2:1 resonance, and more and more spread into the non-resonant region between 42.3 and 47.7 AU; (4) We do not find any distinct difference between objects from the thin disk and the thick disk, after a careful checking.

The stochastic effects in the planetary migration (Zhou et al. 2002) can diminish the 2:1 resonance capture probability and give a possible explanation of the small number of objects in the 2:1 resonance. Ida et al. (2000b) pointed out that a slow migration can enhance the concentration in the 2:1 resonance relative to the 3:2 resonance. Zhou et al. (2002) also found that under the same conditions capture into the 2:1 resonance is more favoured over a longer time-scale (2×10^7 yr) than a shorter time-scale (2×10^6 yr). Our simulations of the long time-scale migration in this paper show that the 2:1 resonance is truly very efficient in trapping objects. When $\beta = 0$ it retains over 44% of the surviving test particles while leaves only about 10% in the 3:2 resonance. In fact, the 2:1 resonance sweeps up the region interior to 39.4 AU of most of the test particles, leaving only a few for the coming 3:2 resonance. However, as β increases the stochastic effect in Neptune’s migration is enhanced, more and more test particles leak out of the 2:1 resonance and some of these are then captured by the following 3:2 resonance. Our simulations prove that, given the proper stochastic effects (i.e., a right sized β and a relatively small standard deviation $\sigma = 0.2$ of the random variable S_n in Equation (2)) and neglecting the Lyapunov time criteria, such a slower and maybe more realistic migration can still reproduce an orbital distribution that well matches the observations; In particular, there are still very few objects trapped in the 2:1 resonance relative to the 3:2 resonance.

In Figures 1 and 2, we can see that the results of the case of $\beta = 48$ agree best with the observations: (1) A large number of the surviving test particles, about 25.6%, are concentrated in the 3:2 resonance, and the absolute size is much larger than in the shorter time-scale case ($\tau = 2 \times 10^6$ yr, Zhou et al. 2002). (2) The orbits in the 3:2 resonance have eccentricities of 0.05–0.3 and inclinations up to 20° , in good agreement with the observations. (3) A small proportion (6.9%) of the test particles falls into the 2:1 resonance, with some of them having high eccentricities and low inclinations. (4) Many test particles survive in the non-resonant region between 42.3 and 47.7 AU and their inclinations can be as high as over 15° . The above outcomes indicate when a long migration time-scale of $\tau = 2 \times 10^7$ yr is adopted, a primordial planetesimal disk beyond Neptune’s orbit can evolve into a configuration finely matching the current KB.

By the way, in our numerical simulations, we also put some test particles in farther orbits with initial semimajor axes $a \geq 48$ AU, but they are not affected by the migration of Jovian planets and kept to their original orbits very well throughout the integration time. So we neglect the region beyond 48 AU in our investigation.

As shown in Figure 2, most test particles remain in relatively low inclination orbits, while a few have their inclinations pumped up to high values. In the case of $\beta = 48$ the inclinations in the 3:2 resonance can reach values above 20° and span a numerical range very close to the observations (Fig. 2a). Moreover, there are also some high-inclination ($> 15^\circ$) test particles in the non-resonant region. These findings suggest that the long time-scale ($\tau = 2 \times 10^7$ yr) migration of the Jovian planets is more efficient in exciting the inclinations. In the next subsection we will provide a detailed analysis on the exciting of orbital inclination.

In the best simulation case of Zhou et al. (2002), none of test particles in the 3:2 resonance have eccentricities smaller than 0.1. However, in our simulations ($\beta = 48$) several objects appear with lower eccentricities (~ 0.05) as the observed Plutinos do. According to the theoretical analysis of Malhotra (1993, 1995), among the objects captured into the resonances, smaller values of a correspond to lower e . This is consistent with our results that these low eccentricity bodies in the 3:2 resonance originated near 39.4 AU.

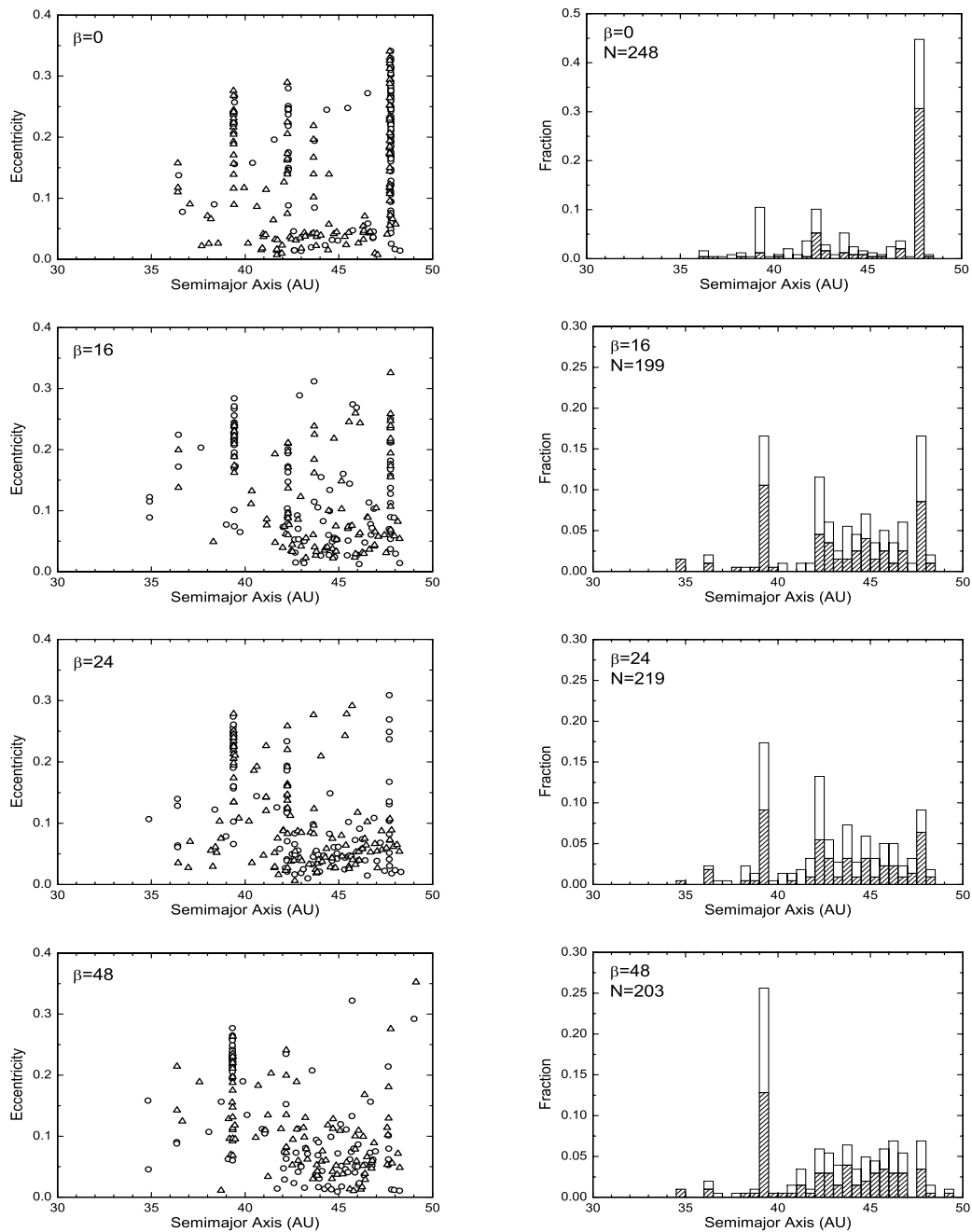


Fig. 1 (Left)—Semimajor axis vs. eccentricity plot for the surviving test particles for the cases of $\beta=0$, 16, 24 and 48. Circles are particles coming from the thin disk, triangles, the thick disk. (Right)—Frequency distribution of the orbital semimajor axes of the surviving test particles originated from the thin disk (shaded) and thick disk (open). The number of surviving particles (out of a total of 400 from the thin and thick disks) is indicated in each panel.

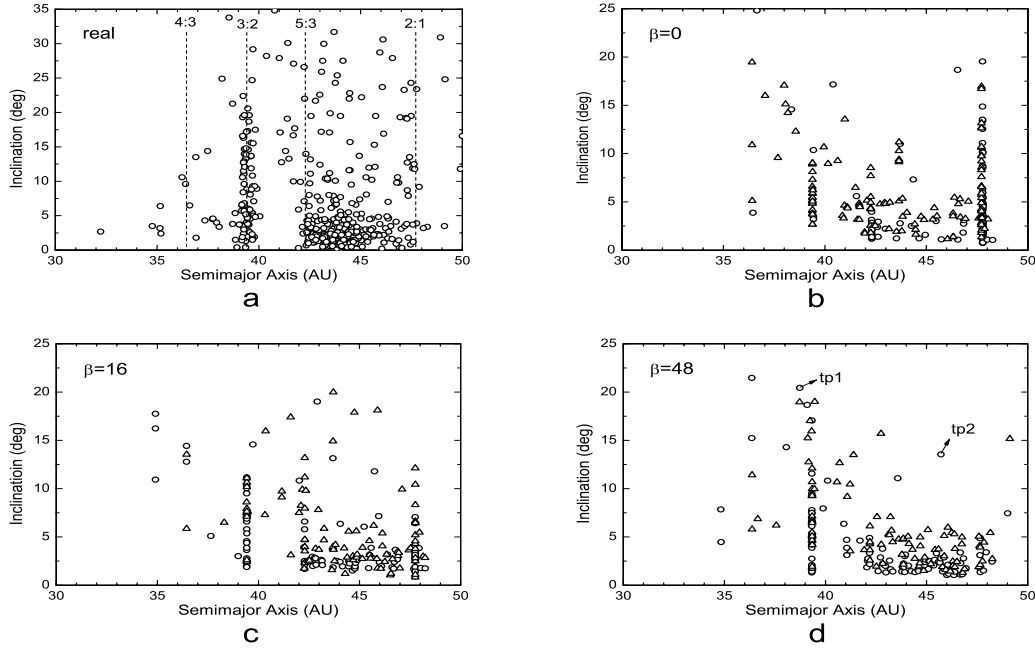


Fig. 2 Panel (a)— Semimajor axis vs. inclination plot for the observed multi-opposition KBOs. The vertical dashed lines indicate some of the MMRs with Neptune. **Panels (b), (c), (d)** refer to cases $\beta = 0, 16$ and 48 . Circles (triangles) represent particles initialized in the thin (thick) disk.

We think that Zhou et al. (2002) may have neglected these low eccentricity particles in their small estimate of the Lyapunov time T_e .

3.2 The Origin of the High-inclination Test Particles

The recent discovery (see footnote 1) of the dynamically ‘hot’ objects with inclinations reaching at least 34° in the KB implies that there could be a dynamically violent process operating in the primordial KB. Understanding what happened to the hot population may provide a crucial clue to the formation and evolution of the outer solar system.

In our results, the inclinations of some test particles are pumped up to high values, so the exciting process needs to be clarified. Now, secular perturbations by the giant planets can excite the orbital eccentricities and inclinations of KBOs. As the closest giant planet to the KB, Neptune plays a particularly important role in the orbital evolution of KBOs. Therefore we focus our investigation on the ν_{18} and ν_8 secular resonances.

When the precession rate of the longitude of ascending node of a test particle matches that of Neptune, the ν_{18} secular resonance arises, causing strong perturbations to the inclination. The linear perturbation theory gives the main term for the time variation of the inclination of a test particle (e.g. Murray & Dermott 1999),

$$\dot{I} = C_1 \sin(\Omega - \Omega_N), \quad C_1 = \frac{nm_N a_N}{M_\odot a \sin I} b_{\frac{3}{2}}^{(1)} \sin\left(\frac{1}{2}I\right) \sin\left(\frac{1}{2}I_N\right), \quad (3)$$

where M_\odot is the mass of the Sun, and m, n, a, I and Ω are the mass, mean motion, semimajor axis, inclination and longitude of ascending node, respectively. The subscript N refers to Neptune and no subscript indicates the test particle. Here $b_{\frac{3}{2}}^{(1)}$ (>0) is the Laplace coefficient. Since both Neptune and the test particle are prograde, we have $0^\circ \leq I, I_N < 90^\circ$ inducing $C_1 > 0$. This implies that $\dot{I} > 0$ and the test particle’s inclination increases when $0^\circ < \Omega - \Omega_N < 180^\circ$, whereas if $180^\circ < \Omega - \Omega_N < 360^\circ$ it decreases.

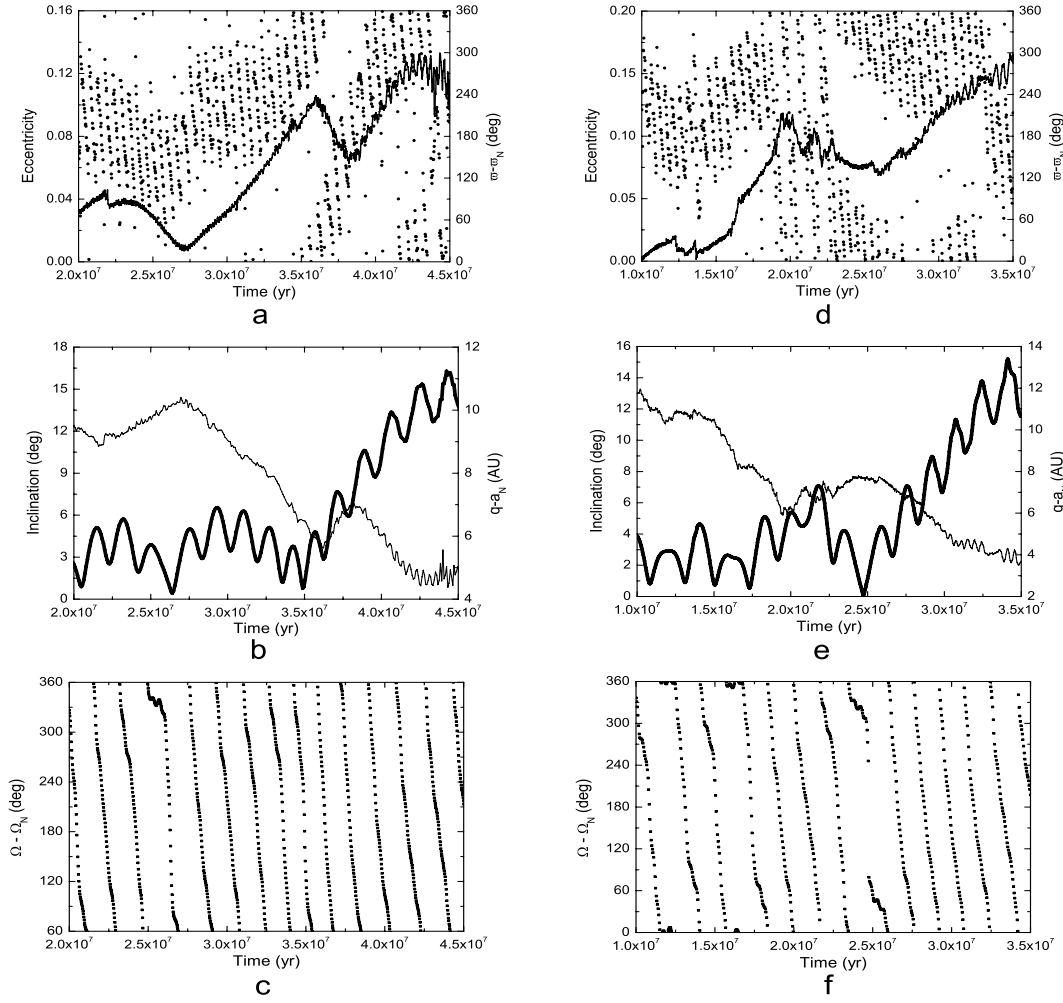


Fig. 3 Orbital evolution of two test particles, tp1 (left column) and tp2 (right column). Upper panels show the time variations of their eccentricities (thick lines) and their perihelion longitudes reckoned from Neptune's (dots). Middle panels are for their inclinations (thick lines) and their perihelion distances, relative to Neptune's semimajor axis (thin lines). Lower panels show their ascending node longitudes, relative to Neptune's.

By carefully checking the evolution of high-inclination ($I > 15^\circ$) test particles, we find that, in all cases, the differences in the longitude of ascending node between the test particle and Neptune ($\Omega - \Omega_N$) circulate (e.g., Fig. 3, lower panels), thus the ν_{18} secular resonance does not take place and cannot be responsible for the excitation of orbital inclination of this high-inclination population.

On the other hand, the 1:1 commensurability in the rate of change of perihelion longitude between a celestial body and Neptune is called the ν_8 secular resonance, and it may lead to an excitation of the orbital eccentricity, described by (e.g., Murray & Dermott 1999)

$$\dot{e} = C_2 \sin(\varpi - \varpi_N), \quad C_2 = -\frac{nm_N a_N e_N}{4M_\odot a} b_{\frac{3}{2}}^{(2)}, \quad (4)$$

where e is the eccentricity, ϖ is the longitude of perihelion and $b_{\frac{3}{2}}^{(2)} (> 0)$ is another Laplace coefficient. Other symbols have the same meaning as in Equation (3). Note that C_2 is a negative number. During the evolution, if $180^\circ < \varpi - \varpi_N < 360^\circ$ then $\dot{e} > 0$, and the eccentricity increases.

Figure 3 shows the evolution of two high-inclination test particles, both for the case of $\beta = 48$. The left column of panels refer to the test particle tp1 (see Fig. 2d) with final semimajor axis 38.73 AU, near but not exactly in the 3:2 MMR with Neptune. Note, from around 2.7×10^7 yr up to 3.6×10^7 yr, tp1 experiences the ν_8 secular resonance, as shown by the librating of $\varpi - \varpi_N$ (dots in Fig. 3a) between 180° and 360° . It leads to a large excitation of the eccentricity (thick line in Fig. 3a), reaching a value about 0.1. At the same time, the difference between the perihelion distance of tp1 $q = a(1 - e)$ and the semimajor axis of Neptune a_N (thin line in Fig. 3b) reaches nearly the minimum value. Bearing in mind that Neptune is always in a near circular orbit, and the small value of $q - a_N$ implies that tp1 could approach Neptune closely. These close encounters can pump up tp1's inclination as Figure 3b (thick line) shows.

The right column of panels in Figure 3 illustrates another example, tp2, ($a \approx 45.71$ AU, see Figure 2d), which is located in the non-resonant region at the end of the integration. The orbital evolution of tp2 is very similar to that of tp1. The eccentricity (thick line in Fig. 3d) was pumped up in $t \approx 2 \times 10^7$ yr by the ν_8 secular resonance and the difference between q and a_N (thin line in Fig. 3e) decreased. Then close encounters with Neptune from $t \approx 2.7 \times 10^7$ yr to $t \approx 3.4 \times 10^7$ yr resulted in the excitation of the inclination (thick line in Fig. 3e).

We should note that a large eccentricity does not guarantee a consequent high inclination: only those objects in orbits not too far away from Neptune's orbit can get high inclinations through the above mechanism. Of course, after the excitations the object may be swept outwards by Neptune's MMR to farther orbits.

In our simulations, the ν_8 secular resonance has a typical period of $\mathcal{O}(10^5)$ yr. Therefore, if the migration time-scale of the planet is shorter than or comparable to this period, then a quick migration will stifle the secular resonance. Only a sufficiently long migration time-scale much longer than the period of the secular resonant perturbations can make the secular resonances such as ν_8 effective. We think that is a possible explanation why the long time-scale ($\tau = 2 \times 10^7$ yr) migration is more efficient in exciting the orbits of the test particles.

Another mechanism that may efficiently excite the inclination is the so-called Kozai resonance. A well known example is its contribution to Pluto's inclination (Wan et al. 2001). In our simulations, however, we did not find the existence of the Kozai resonance.

We have discarded all test particles that have entered any planet's Hill sphere in our numerical simulations. In fact, some of them may still have survived (e.g., as scattered KBOs) after their orbits being strongly excited by close approaches to the giant planets. If these objects are taken into account, then the relative population of high-inclination objects will be even larger.

4 CONCLUSIONS AND DISCUSSION

The Jovian planets might experience orbital migrations in the late stages of planetary system formation. A series of numerical simulations (Fernández & Ip 1984; Malhotra 1995; Hahn & Malhotra 1999) suggest that the migration is relatively slow with a time-scale of $\mathcal{O}(10^7)$ yr. Moreover, the migration is not smooth, rather, it is characterized by a 'to-and-fro' dancing movement.

We modelled this orbital migration by adding an artificial, random drag force on the planet to drive its stochastic component. We adopted a migration time-scale $\tau = 2 \times 10^7$ yr, and numerically followed the orbital evolution of a large number of test particles initialized between 28 and 47.9 AU. Our numerical results show that, under the long time-scale and stochastic migration of the Jovian planets, these test particles can evolve to a distribution that is very similar to the currently observed KB.

In a slow migration Neptune's MMRs are very efficient in trapping the test particles, but the stochastic effects drive numerous test particles out of the 2:1 resonance during the outward migration. Part of these 'refugees' are picked up by the following 3:2 resonance and some of them enter the region of the classical KBOs. With a stochastic effect of the right magnitude ($\beta = 48$), the concentration in the 3:2 resonance is still well kept up while the 2:1 resonance is largely depleted, and the final radial distribution of the test particles matches the observational data of KBOs very well. Of the objects in the 3:2 resonance the distributions of eccentricities (in the range 0.05–0.3) and inclinations (in 0 – 20°) resemble the observed distributions of the real Plutinos.

We also find that those test particles with initial $a \geq 48$ AU, beyond the current location of the 2:1 resonance, suffer negligibly weak perturbations of the Jovian planets and hold their orbits very well throughout the integration. This implies if there were objects in this region, they cannot be depleted by the planetary

migration, but only very few observed KBOs have semimajor axes larger than 48 AU. This outer fringe of the KB should be explained by some other mechanisms, e.g., early stellar encounters (Ida et al. 2000a; Melita et al. 2005).

In our simulations of the 400 objects starting from 28 to 47.9 AU, the number of survivors is always found to be around 200 for all five values of β (8, 16, 24, 32 and 48). This $\sim 50\%$ survival rate is in conflict with the significant mass deficiency of the present KB. Petit et al. (1999) suggested that larger planetesimals with masses from a few tenths to one Earth mass could have ejected most of the objects from the primordial KB. It is worthwhile to include this mechanism in our model in future.

The inclinations of some test particles in our simulations can attain values up to 20° . Our analyses have revealed the excitation process: the eccentricity is pumped up by the ν_8 secular resonance, decreasing the perihelion distance, and then the inclination is excited by close encounters with Neptune. The ν_{18} secular resonance may account for the inclination excitation, but none of the high-inclination test particles in our simulations is produced by this mechanism. However, we notice that Brasser et al. (2004) showed an example (Neptune Trojan 2001 QR322) of inclination increase so caused.

Gomes (2003) proposed that the high-inclination KBOs may originally come from an inner region of the primordial planetesimal disk around 25 AU. As Neptune migrates outwards, the planetesimals are scattered to the current orbits and obtain high inclinations by close encounters with Neptune. Our numerical simulations reveal a possible mechanism of exciting objects that are not in the inner region of the primordial disk and not so close to Neptune originally.

However, our results are only numerical and theoretical analyses concerning the physical meaning of the magnitude of the stochastic effects in the planetary migration, and the detailed process of the close encounter between the object and Neptune, etc., should be carried out in the future.

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