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The effect of the giant planets on the dynamical evolution of the mutual orbits of trans-Neptunian binaries

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ABSTRACT
The action of tidal friction, coupled with the Kozai cycles, drastically changed the original orbits of trans-Neptunian binaries (TNBs). The dynamics of the Kozai mechanism is driven by the solar torque on the mutual orbit, so that the orientation of the latter relative to the heliocentric orbital plane plays a fundamental role in this process, both in the magnitude and in the characteristic of the cycles. In this way, any effect that makes this relative orientation vary may be relevant in the dynamics of the process. In this paper, we will focus on the effect that the perturbations of the giant planets on the heliocentric orbit of TNBs have on the dynamics of the Kozai cycles and tidal friction. For this task, we have performed numerical simulations of the evolution of a synthetic population of TNBs subject to Kozai cycles and tidal friction adding planetary perturbation on their heliocentric orbits. We found that in a non-negligible fraction of cases (∼25 per cent), this additional perturbation produces substantial changes in the orbital evolution. The slow precession of the heliocentric orbit and the variation of its inclination can make the dynamical evolution of the mutual orbits very irregular, completely changing the morphology of the Kozai cycles. When these variations are coupled to tidal friction, the lifetime of the TNBs can change substantially.

Key words: comets: general – Kuiper belt: general.

1 INTRODUCTION

Trans-Neptunian binaries (TNBs) have received increasing attention in recent years because they keep valuable information about the processes that occurred during the formation of the outer Solar system. Understanding the evolution of TNB orbits is relevant to reveal the mechanism that gave rise to them, their dynamic stability against different factors, and fundamentally, to reconstruct the characteristics of the primordial population from what is observed today.

The evolution of the mutual orbits of TNBs can be modelled fairly closely by Kozai's secular theory (Kozai 1962; Lidov 1963). The mutual orbit of the binary and the heliocentric orbit of its centre of mass exchange angular momentum, while the orbital energy remains almost unchanged. Thus, while the semi-axis of the binary mutual orbit does not change, the inclination and the eccentricity vary in a way known as the Kozai mechanism: a coupled cycle where when one increases the other decreases to keep the angular momentum constant. The relative inclination between the binary orbit and the orbital plane of the perturbing body is a crucial factor in determining the strength of the Kozai effect and the resulting dynamical evolution of the binary. In general, the Kozai effect is strongest when the relative inclination is near 40° or 140°, which are known as the Kozai critical angles (Kozai 1962). At these relative inclinations, the binary eccentricity can reach its maximum value and the pericentre distance can experience significant changes. In contrast, when the relative inclination is near 0° or 180°, the Kozai effect is weak and the binary eccentricity and inclination remain relatively constant over time.

Another key process that governs the evolution of TNBs is tidal friction, which is the transfer of angular momentum from the binary system to the individual components due to the interaction between the tidal bulges raised by one body on the other (Hut 1981; Eggleton & Kiseleva-Eggleton 2001). Over time, this process may cause the semimajor axis of the binary orbit to shrink, leading to the eventual merging of the two bodies into a single entity. The efficiency of tidal friction depends on various factors, such as the size and internal structure of the binary components and the strength of their gravitational interaction (Goldreich & Soter 1966). However, the tidal friction time-scale depends strongly on the separation of the binaries, and in the case of very eccentric orbits, the tidal interaction acts as kicks at pericentre (Hut 1981). Therefore, the important parameter to measure the relevance of tidal forces is the pericentre distance rather than the semi major axis. In this context, the oscillations of the orbital eccentricity by the Kozai mechanism play a key role in the orbital evolution of TNBs (Porter & Grundy 2012; Brunini & Zanardi 2016).

The Kozai mechanism is closely associated with the orbital precession rate (Innanen et al. 1997) so that the existence of small perturbations to the system that modify this precession rate can substantially alter the dynamics of the Kozai cycles and even suppress them. The effect of some sources of additional perturbations was analysed in the literature. In the context of TNBs, the effect of the oblateness of the binary components was investigated by Porter & Grundy (2012) and also by Brunini & Zanardi (2016). In these works,

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it was shown that this effect may be important for binaries with very closed orbits. Relativistic precession (Fabricky & Tremaine 2007) was also extensively studied. Although this effect is important for objects orbiting a central star perturbed by an inner eccentric planet (Zanardi et al. 2018), hot planets in extrasolar planetary system, and some stellar objects, it seems not to be relevant for the evolution of TNBs.

In this work, we will focus on possible effects that the inclusion of the giant planets could have on the orbital evolution of TNBs. The effect of additional bodies on the Kozai mechanism was analysed in several situations like planets orbiting binary stars (Innanen et al. 1997; Wu & Murray 2003; Malmberg, Davies & Chambers 2007) or orbiting triple stellar systems (Marzari & Barbieri 2007), which are not directly applicable to Kuiper Belt Objects (Hereafter KBOs). The most closely related to our scope is the model by Fang, Thompson & Hirata (2018). They developed a secular theory for the case of quadruple stellar systems composed of two tight binaries. The conditions imposed to obtain this secular model are not entirely applicable to our case (although they will help us to understand some relevant aspects of the problem).

This paper is organized as follows: in Section 2, we will present a brief discussion about the secular equations that will be used in our simulations, and we will analyse the strategies to be applied to evaluate the influence of planetary perturbations on the orbital dynamics of TNBs. Section 3 will be dedicated to present the initial conditions and the methods used to carry out the simulations. In Section 4, we will show the most relevant results, and Section 5 will be devoted to the conclusions.

2 THE KOZAI MECHANISM AND THE ROLE OF PLANETARY PERTURBATIONS

Although they can be found in the literature, for reasons of completeness, we will present here, in a very synthetic way, the secular equations that govern the evolution of a TNB. For binary minor planets like TNBs, the heliocentric orbit of the centre of mass contains most of the angular momentum. In this situation, the Hamiltonian up to the quadrupole order [up to the order $(a/a_\odot)^2$, where a is the semimajor axis of the mutual orbit and $a_\odot$ is the semimajor axis of the heliocentric orbit of the binary centre of mass] averaged over the mean anomalies is (Innanen et al. 1997; Fabrycky & Tremaine 2007)

$$H_{\rm quad} = \frac{G m_\odot a^2}{8 a_\odot^3 (1-e_\odot^2)^{3/2}} [2+3e^2 - (3+12e^2-15e^2\cos^2\omega)\sin^2 i], \tag{1}$$

where G is the gravitational constant, $m_\odot$ is the solar mass, $e_\odot$is the eccentricity of the heliocentric orbit, e is the eccentricity of the mutual orbit, ω the argument of periastron and i is the inclination of the binary orbit relative to the plane of the heliocentric orbit. Scaling the time by writing

$$t = (1-e_\odot^2)^{3/2} \frac{P_\odot^2}{2\pi P_{\rm bin}} \tau, \tag{2}$$

where $P_{\rm bin}$ and $P_\odot$ are the periods of the mutual orbit and of the heliocentric orbit, respectively, the secular equations of motion can be written as

$$\frac{{\rm d}e}{{\rm d}\tau} = \frac{15}{8} e\sqrt{1-e^2}\sin(2\omega)\sin^2(i), \tag{3a}$$

$$\frac{{\rm d}i}{{\rm d}\tau} = -\frac{15}{8}\frac{e^2}{\sqrt{1-e^2}}\sin(2\omega)\sin(i)\cos(i), \tag{3b}$$

$$\frac{{\rm d}\omega}{{\rm d}\tau} = \frac{3}{4}\sqrt{1-e^2}\{2(1-e^2)+5\sin^2(\omega)[e^2-\sin^2(i)]\}, \tag{3c}$$

$$\frac{{\rm d}\Omega}{{\rm d}\tau} = -\frac{\cos(i)}{4\sqrt{1-e^2}}[3+12e^2-15e^2\cos^2(\omega)]. \tag{3d}$$

As in Brunini & Zanardi (2016) equation (2) and (3a)–(3d) were used throughout this paper to model the Kozai dynamics of TNBs.

The time-scale of the Kozai oscillations is (Eggleton & Kiseleva-Eggleton 2001)

$$T_K \simeq \frac{t}{\tau}. \tag{4}$$

$H_{\rm quad}$ is a conserved quantity (Fabrycky & Tremaine 2007) and it is independent of Ω, the longitude of the ascending node. Therefore, the conjugate canonical variable

$$J_z = \sqrt{1-e^2}\cos i \tag{5}$$

is also a conserved quantity. This implies that when the eccentricity achieves its maximum value, the inclination is at its minimum (and vice versa). From equation (3a), the maximum eccentricity is achieved when $\omega = 0^\circ$ or 270°. For orbits with an initial eccentricity $e = 0$, it is found that (Innanen et al. 1997)

$$e_{\rm max} = [1-(5/3)\cos^2(i_{\rm ini})]^{1/2}. \tag{6}$$

Therefore, if the initial inclination is above the critical value

$$i_{\rm crit} = \arccos(3/5)^{1/2} \simeq 39.2^\circ \text{ or } 140.8^\circ, \tag{7}$$

then $e_{\rm max}$ may be very large (Kozai 1962). For binaries of the Classical Kuiper Belt population, the eccentricity of the heliocentric orbits may be of up to $e_\odot \simeq 0.25$ (for the hot population). Under these conditions, we could ask ourselves to what extent the quadrupole approximation for the secular Hamiltonian is enough to study the dynamical evolution of these objects. The relevance of the octupole terms, in relation to the quadrupole ones, is defined by the parameter (Naoz 2016)

$$\epsilon = \frac{a}{a_\odot}\frac{e_\odot}{1-e_\odot^2}. \tag{8}$$

For a binary with $a = 20\,000$ km, whose heliocentric orbit has $a_\odot = 45$ au and $e_\odot = 0.25$, we have $\epsilon \simeq 8\times 10^{-7}$. Therefore, we conclude that the quadrupole approximation for the Hamiltonian is accurate enough to study the dynamical evolution of the mutual orbits of these objects.

As shown by equation (3a), the rate of change of orbital eccentricity is proportional to $\sin 2\omega$, and additional effects leading to pericentre precession of the binary orbit can suppress Kozai cycles. Among the already studied effects, we have relativity, tides, rotational distortion of the central body, and the presence of extra bodies (Fabrycky & Tremaine 2007; Porter & Grundy 2012). For the case of TNBs, the effect of tides was largely analysed (Porter & Grundy 2012; Brunini & Zanardi 2016; Brunini 2020) and in fact it will be included in most of our simulations because it is the most important one for TNB evolution. In this work, we will focus on possible effects that the inclusion of the giant planets could have on the orbital evolution of TNBs.

As it was already mentioned, the effect of additional bodies in the context of Kozai secular dynamics was analysed in several situations like planets orbiting binary stars (Innanen et al. 1997; Wu & Murray 2003; Malmberg et al. 2007) or orbiting triple stellar systems (Marzari & Barbieri 2007). The particular characteristics of the investigated objects differ from those of the TNBs and therefore the reported results cannot be extended to these objects. Fang et al.

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(2018) developed a secular theory for the case of quadruple stellar systems composed of two tight binaries. If the mutual separations of each binary subsystem are r_1 and r_2 and the centres of masses of each binary subsystem are separated by a distance r, in their model, Fang et al. (2018) assumed that r_1, $r_2 \ll r$. In our case, one of the binaries would be composed of the Sun and a planet (denoted with $m_\odot$ and m_p, respectively) separated a distance r_p, and the other binary would be a TNB. If the mass of the other binary is $m_\mathrm{bin} \ll m_\mathrm{p}$, we can consider that the planet is on a fixed elliptical orbit, and as the centre of mass of the Sun–planet sub-system is very small compared to r_p, we may consider for this preliminary analysis that the orbit of the centre of mass of the binary is its heliocentric orbit. The reference plane is the plane perpendicular to the total angular momentum of the system, and as $m_\mathrm{bin} \ll m_\mathrm{p}$, it is not too inaccurate for the moment to adopt as the reference plane the orbital plane of the planet around the Sun. The secular Hamiltonian for the binary mutual orbit, up the quadrupole order in $a/a_\odot$, is (Fang et al. 2018)

$$\begin{aligned} H_1 = &\alpha_1 3\sin^2 i_\odot [10e^2(3+\cos 2i)\cos 2\omega + 4(2+3e^2)\sin^2 i] \\ &\times \cos 2(\Omega - \Omega_\odot) \\ &+ 12(2+3e^2-5e^2\cos 2\omega)\sin 2i_\odot \sin 2i \cos(\Omega-\Omega_\odot) \\ &+ 120e^2 \sin 2\omega \sin 2i_\odot \sin i \sin(\Omega-\Omega_\odot) \\ &- 120e^2 \sin 2\omega \sin^2 i_\odot \cos i \sin 2(\Omega-\Omega_\odot)\}, \end{aligned} \tag{9}$$

where

$$\alpha_1 = \frac{G}{128(1-e_\odot^2)^{3/2}} \frac{(m_\odot + m_p)m_1 m_2}{m_\mathrm{bin}} \frac{a^2}{a_\odot^3}, \tag{10}$$

where Ω and $\Omega_\odot$ are the longitude of the ascending nodes of the mutual orbit and of the heliocentric orbit of the binary respectively. To simplify the analysis, let us consider the particular case of an equal-mass binary ($m_1 = m_2$). Within this assumption, the mutual orbit of the binary is affected by the planet through a term proportional to

$$\alpha_1^p = \frac{G}{508(1-e_\odot^2)^{3/2}} m_p m_\mathrm{bin} \frac{a^2}{a_\odot^3}. \tag{11}$$

The contribution of the planet to the secular evolution of the ascending node (taken as an example of the secular evolution of the orbit) is

$$\dot{\Omega} = -\frac{3}{64(1-e_\odot^2)^{3/2}} \frac{m_\mathrm{p}}{m_\odot} \frac{n_\odot^2}{n} f_1(e^2, i, \omega, \Omega), \tag{12}$$

where $f_1(e^2, i, \omega, \Omega)$ is a function of order 1.

The planet also affects the heliocentric orbit of the binary. To evaluate this effect, we will use the secular Hamiltonian for the evolution of the heliocentric orbit of a test particle (which for our case is the centre of mass of the TNB) around an inner binary (the Sun–planet system) (Naoz et al. 2017). In this case, the change rate of the ascending node of the heliocentric orbit is given by

$$\dot{\Omega}_\odot = -\frac{3}{4(1-e_\odot^2)^2} \frac{m_\mathrm{p}}{m_\odot} n_\mathrm{p} \left(\frac{a_\mathrm{p}}{a_\odot}\right)^2 f_2(e^2, i, \omega, \Omega), \tag{13}$$

where, as before, $f_2(e^2, i, \omega, \Omega)$ is a function of order 1.

Therefore using equations (12) and (13) we have

$$\frac{\dot{\Omega}}{\dot{\Omega}_\odot} = \frac{1}{16} \frac{P_\mathrm{bin} P_\mathrm{p}}{P_\odot^2} \left(\frac{a_\mathrm{p}}{a_\odot}\right)^2 \sqrt{(1-e_\odot^2)} \times (f_1/f_2), \tag{14}$$

where P_p is the period of the heliocentric orbit of the planet. Taking values of P_bin from the known population of binaries of the Classical Kuiper Belt and Neptune as a perturbing object, we have

$$\dot{\Omega}/\dot{\Omega}_\odot = 5 \times 10^{-2} - 2 \times 10^{-7}. \tag{15}$$

We conclude that the variation of the heliocentric orbit of the TNBs induced by the planetary perturbation is the dominant one. We can also conclude that the orientation of the mutual orbit with respect to a fixed reference system does not change substantially due to these perturbations. The question now is how these variations of the heliocentric orbit affect the mutual orbit because the Kozai cycles depend on the relative inclination, and the strength of the cycles is driven by the precession of the argument of periastron and the mutual inclination. This indirect variation of the orientation of the mutual orbit is illustrated in Fig. 1

The osculating heliocentric orbit of the binary centre of mass at time t is represented by the ellipse $\odot$. Due to the planetary perturbations, after a period of time h the osculating orbit changes to the ellipse $\odot'$. The longitude of the ascending node changes by an amount $\Omega'_\odot - \Omega_\odot$, and the orbital inclination with respect to the inertial reference system changes from i to i'. This is reflected in the inclination, the longitude of the ascending node, and the argument of the periastron of the binary mutual orbit. The new coordinates at time $t + h$ are related to the old coordinates at time t by the rotation matrices (see e.g. Nie & Gurfil 2021)

$$\mathbf{R}(t + \mathrm{d}t) = [i'_\odot]_x [\Omega'_\odot - \Omega_\odot]_z [-i_\odot]_x \mathbf{R}(t), \tag{16}$$

where $[\theta]_\beta$ is a rotation matrix corresponding to the rotation of an angle θ around the β axis.

The initial conditions of the objects that we explore in this work will be discussed in the next section. However, it is interesting to mention that for the heliocentric orbits that we will study, corresponding to objects of the hot classical population of the Kuiper belt, the main frequencies of the orbital elements range from $\sim 7 \times 10^6$ to 2×10^7 yr. These are longer than the characteristic times of the Kozai oscillations of the mutual orbits, so we would not expect a very large effect. Nevertheless, let's take for example a TNB at 45 au from the Sun, with two components of equal diameter $D = 200$ km and a semi-axis of 20 000 km. According to equation (4), $T_k \simeq 20\,000$ yr. If instead the semi-axis is reduced to 1000 km, then $T_k \simeq 1.7 \times 10^6$ yr, which is within the range of the precession periods of the heliocentric orbits. (For the mutual orbits of the binaries that we will explore in this paper, the periods of the Kozai oscillations are generally in the range of 5×10^4 to 5×10^5 yr, but in a few cases they reach $\sim 10^6$ yr.) In this way, at some point during the orbital evolution, the planetary perturbations on the heliocentric orbit could produce appreciable effects on the dynamics of TNBs. In principle, we will not be able to anticipate what will happen throughout the entire evolution of a given object without first knowing how the orbit will evolve. For this reason, it is necessary to explore whether planetary perturbations can effectively affect the evolution of TNBs.

We have two ways to address this problem. One way is to use the secular theory of Fang et al. (2018) for the entire system. However, it is limited for our study because it was developed under the hypothesis that $a_\mathrm{bin} \ll a_\mathrm{p} \ll a_\odot$. In our case, the last condition is no longer fulfilled. For example, in the case of a TNB and Neptune as a perturbing planet we have $a_\mathrm{p}/a_\odot \sim 2/3$. Therefore, the secular Hamiltonian, up to the hexadecapole order (the maximum order found in Fang et al. 2018), is not appropriate to describe the contribution of the planets on TNBs, and we would need to use a very high order expansion. In this case, the numerical integration of these sets of secular equations would not offer a clear advantage in relation to a direct numerical integration of the equations of motion of the heliocentric orbit. Even more so if we included in the simulation the perturbations of the four giant planets, because then the planetary orbits would stop being fixed ellipses. Short period disturbances could appear that would affect the orbits of the TNBs in a way that is

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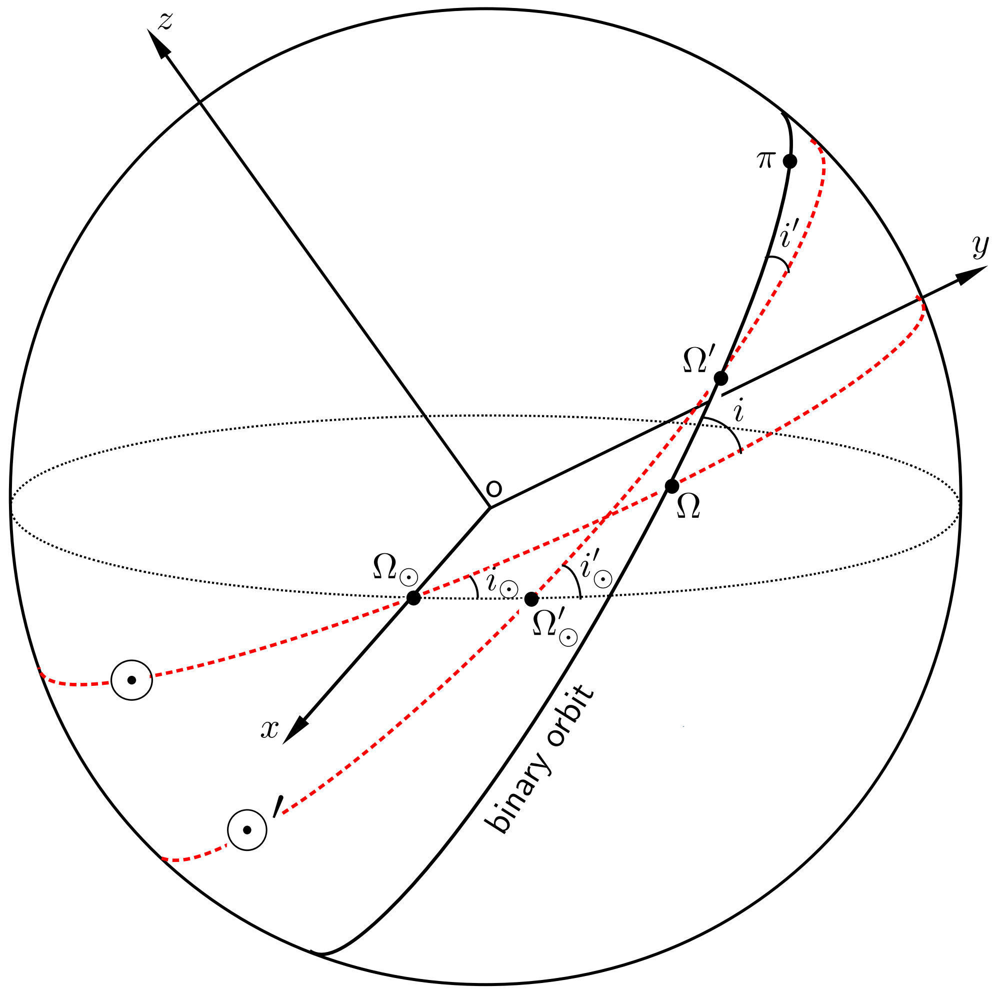

Figure 1. A variation in the heliocentric orbit is reflected in the orientation of the mutual orbit with respect to it.

difficult to predict. For these same reasons, we decided not to use the equations of the secular theory for an outer test particle perturbed by an inner planet (Naoz et al. 2017). Therefore, to consider the effect of planetary perturbations on the heliocentric orbit of the TNBs, and their potential to affect the dynamics of the Kozai cycles of the mutual orbits, we have decided to perform a numerical integration of the heliocentric orbits, which we have carried out with the code evorb (Fernández, Gallardo & Brunini 2002) in barycentric coordinates. We used the rotations given by equation (16) to evaluate the changes of the mutual orbit.

3 INITIAL CONDITIONS

In this section, we will present the set of initial conditions and parameters used in our simulations. The classical population of KBOs (Lykawka & Mukai 2005) is composed of those objects whose heliocentric orbits have semi-axes between the 3:2 and 1:2 mean-motion resonances with Neptune, and perihelion distances that ensure they do not undergo close encounters with Neptune. Within this population, two subgroups can be distinguished: the cold population, which has low orbital inclinations ($i \leq 5^{\circ}$), and the hot population, which was probably implanted during Neptune's orbital migration process, with higher inclinations ($i > 5^{\circ}$). In this work, we have taken some of the orbital elements published in the Minor Planet Center data (Williams et al. 2022) base for the trans-Neptunian objects belonging to the population of the Hot Classical Kuiper Belt, as the initial heliocentric orbit of the centres of mass of the binary objects. To do this, we restrict the sample, somewhat arbitrarily, to objects with 43 au $\leq a_{\odot} \leq$ 47 au, $i_{\odot} \geq 5^{\circ}$, and $q_{\odot} \geq$ 36 au. With these conditions, we were left with 614 objects, but to make the simulations feasible with our computational resources, we randomly took 120 of them, which we used throughout the entire work.

We have generated the initial conditions of the binary systems to make them realistic, and in that sense we closely follow previous simulations found in the literature (Porter & Grundy 2012; Brunini & Zanardi 2016). However, as our main interest is to analyse whether giant planets play any role in the dynamical evolution of TNB objects rather than to contrast the results with the observed orbital characteristics, we have not exhaustively explored the entire possible universe of parameters. Although the initial conditions were generated with the same criteria as in Brunini & Zanardi (2016), for reasons of completeness, we will give here a brief description of the procedure used.

Let us define the binary's Hill radius as

$$r_{\rm H} = a_{\odot}(1 - e_{\odot})\left(\frac{m_{\rm bin}}{3m_{\odot}}\right)^{1/3}. \tag{17}$$

The semi-major axis of the mutual orbit was generated at random, with uniform distribution from 1 to 10 per cent of the system's Hill radius. The orbital eccentricity was also taken at random in

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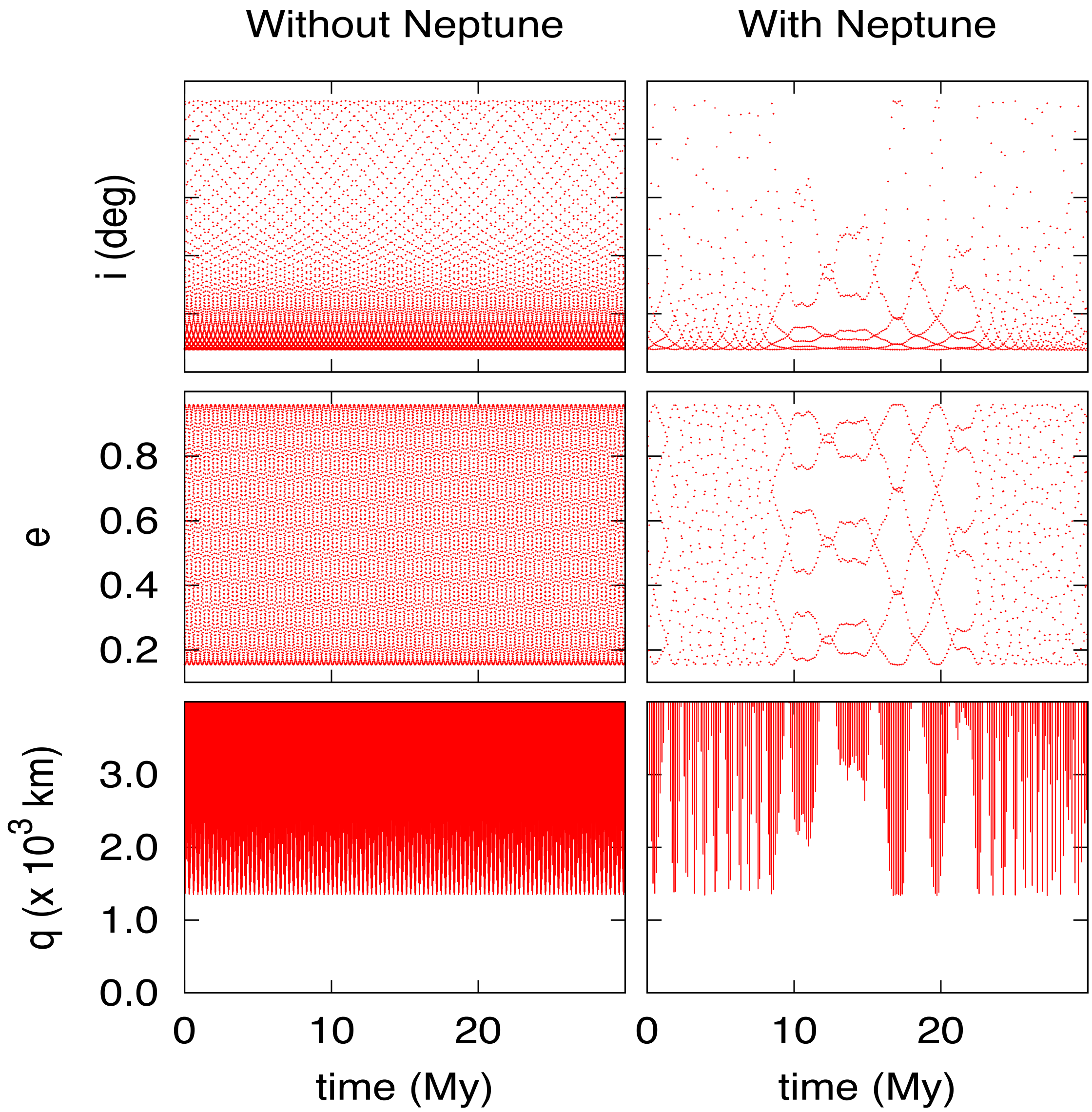

Figure 2. In the top panels, the evolution of the mutual inclination of the binary is shown with and without the presence of Neptune. The middle panels show the same but for eccentricity and the bottom panels depict the evolution of the pericentre distance. In these last panels, only the region with $q \leq 4000$ km is shown. Tidal friction is not included in this simulation.

the interval with uniform distribution. Both semimajor axis and eccentricity were chosen so that the pericentre distance of the binary is larger than the Roche distance, defined as

$$R_{\mathrm{Roche}} = 1.26(R_1 + R_2), \tag{18}$$

where R_1 and R_2 are the radii of the binary components. The mean anomaly, argument of the pericentre, and longitude of the ascending node were generated at random with uniform distribution in the interval [0, 2π]. For each binary system, the diameter of the components was generated at random within the range 60 km $\leq D \leq$ 200 km, with a density of $\rho = 1g$.

In those cases where tidal friction was included, we used the same code as Brunini (2014), based on the model developed by Eggleton & Kiseleva-Eggleton (2001), whose equations are summarized in Fabrycky & Tremaine (2007). The physical parameters for the tidal evolution model were the same used by Porter & Grundy (2012) and Brunini & Zanardi (2016). In all the cases, we adopted the canonical values for icy homogeneous solid bodies of $Q = 100$, and the second tidal Love number K_L

$$K_{\mathrm{L}} = \frac{3}{2}\left(1 + \frac{19\mu_r R}{2Gm\rho}\right), \tag{19}$$

was computed with a rigidity of $\mu_r = 4 \times 10^9\,\mathrm{Nm}^{-2}$. The spin periods were taken at random in the interval $2h \leq$ spin period $\leq 48h$ and the orientation of the spin axes was at random in the interval [0°, 2π].

In all cases, the simulation stops if any of the following conditions is verified:

(i) Survival during all the time span covered by the simulation.
(ii) Separation of the components, because either the orbit becomes hyperbolic or the semimajor axis becomes larger than $0.5R_{\mathrm{H}}$.
(iii) Collision between the components, when the pericentre distance becomes shorter than the mutual Roche radius.

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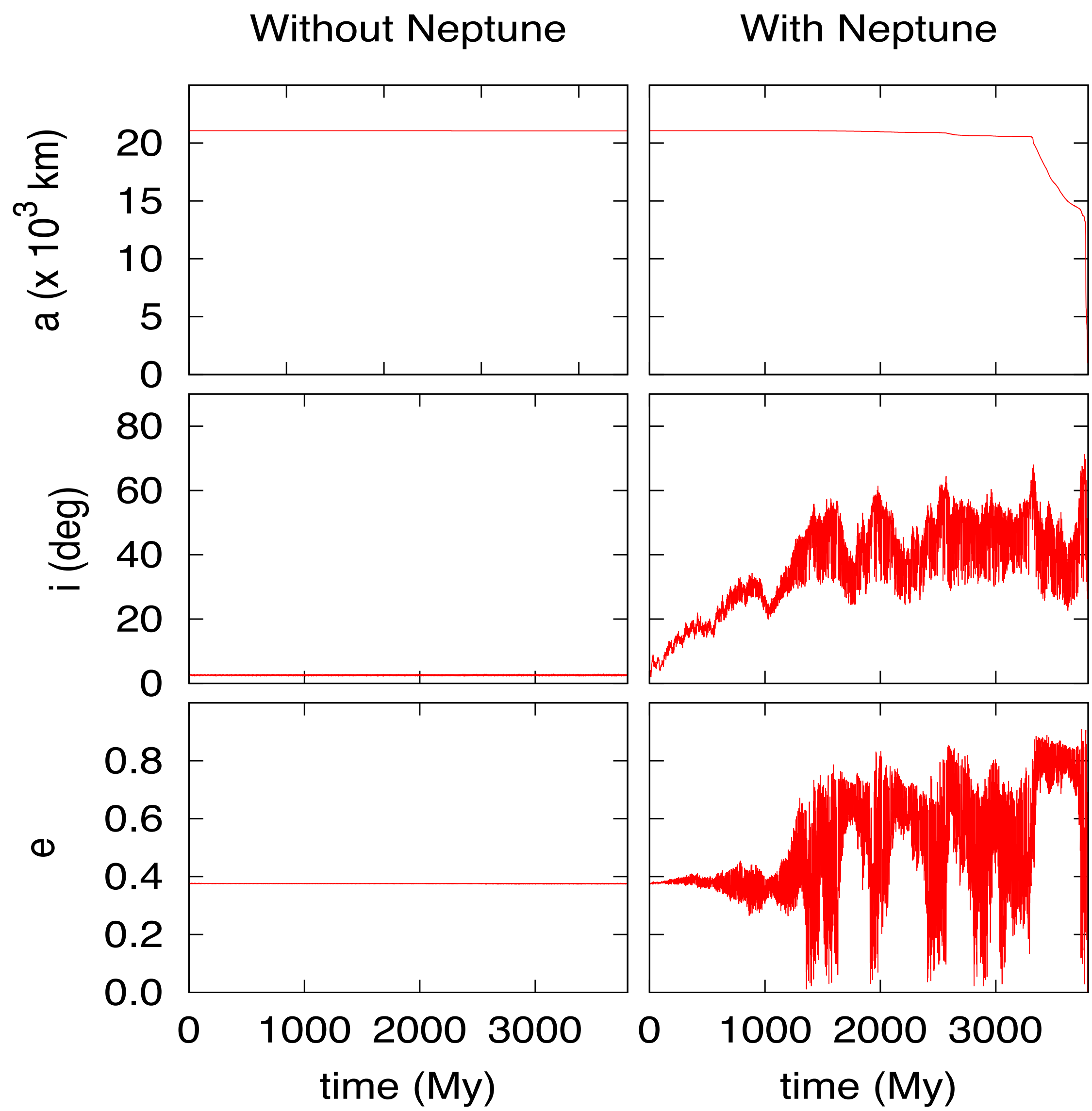

Figure 3. In the top panels, the evolution of the mutual inclination of the binary is shown with and without the presence of Neptune. The middle panels show the same but for the mutual inclination and the bottom panels depict the evolution of the pericentre distance. In this case, the presence of Neptune shortens the lifetime of the object. Tidal friction is included in the model.

It is worth mentioning that within the selected heliocentric orbits, there are 14 that correspond to binary objects of the classical hot population. However, the mutual orbits we explored do not correspond to the orbits of the true binaries, since they were generated, like all of them, randomly.

4 RESULTS

In Fig. 2, we show the secular evolution of the orbit of a TNB subject to the solar perturbation with and without the presence of Neptune (in this case, we have only included in the model the perturbations that Neptune exerts on the heliocentric orbit of the centre of mass of the binary) and not considering any other effect such as tidal friction.

We can observe that in the case without Neptune the Kozai cycles are regular, while the inclusion of an additional disturbing body destroys this feature. This is not surprising, since the secular equations of motion including up to the quadrupole order are integrable (Kinoshita & Nakai 2007), a quality that disappears when an additional body is included. The small differences in the evolution of the mutual inclination, which are reflected in the eccentricity of the orbit of the binary, cause an appreciable change in the behaviour of the pericentre distance, which could have appreciable consequences if the evolution by tidal friction were also included in the model. This is not the case of this particular binary. In fact, in ∼75 per cent of the cases, even including tidal friction in the model, the evolutions of the mutual orbits are qualitatively similar. However, we found that in ∼25 per cent of the cases, the evolution differs substantially. Two of them are depicted in Figs 3 and 4. In both cases, the evolution is qualitatively different.

In Fig. 3, we can observe that the evolution without the inclusion of Neptune is very regular during the entire evolution of 4.5×10^9 yr. When Neptune is included, the evolution becomes more and more irregular (we prefer not to call it chaotic, since we have not applied any chaos indicator). A certain orbital diffusion leads to

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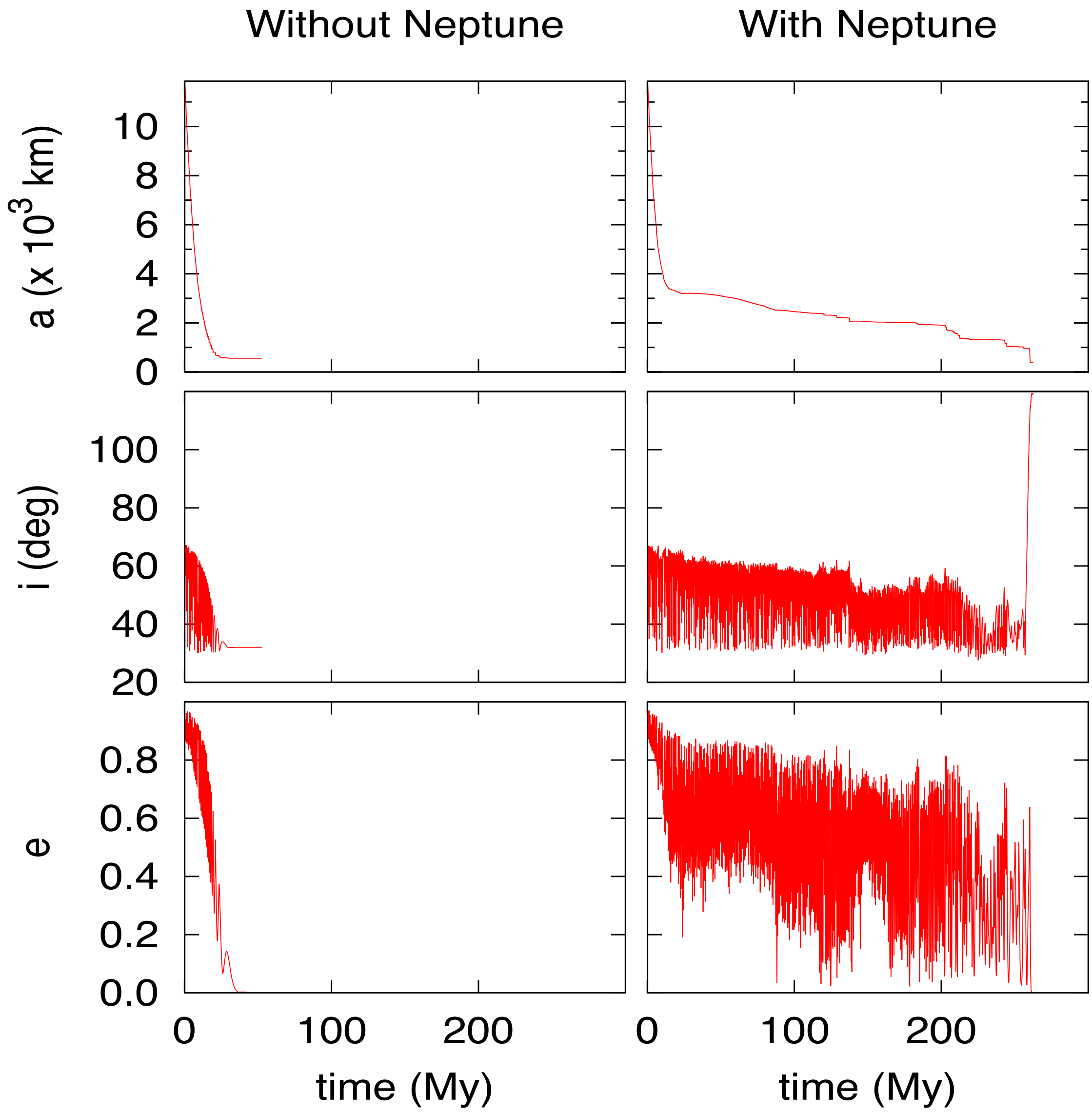

Figure 4. In the top panels, the evolution of the mutual inclination of the binary is shown with and without the presence of Neptune. The middle panels show the same but for the mutual inclination and the bottom panels depict the evolution of the pericentre distance. In this case, the lifetime of the object is extended by the presence of Neptune. Tidal friction is included in the model.

the inclination towards the region close to the critical Kozai angle, and then the eccentricity acquires very large values. Although the object remains bound during almost the entire evolution, it is noted that during the last $\sim 5 \times 10^8$ yr the action of the tides begins to drastically reduce the pericentre distance. The object will end up as a contact binary.

In Fig. 4, we can observe a typical evolution of a binary with a moderate separation but with an initial eccentricity high enough so that the action of the tides quickly reduces its separation until it becomes a contact binary. However, when Neptune is included, the orbital eccentricity presents large fluctuations that weaken this process. Although the end state is the same in both cases, the object lasts much longer as a binary when Neptune's perturbations on the heliocentric orbit are considered, a behaviour that is the opposite of that shown in Fig. 3. Although a complete analysis of the dynamics of the four body problem is extremely difficult, we try the following explanation for the behaviour that is observed: as we have stated above, the small oscillations in the inclination of the heliocentric orbit have a period much longer than that of Kozai oscillations. This causes the angular momentum vector of the mutual orbit to accommodate adiabatically as the heliocentric orbit evolves. Eventually, this process leads the mutual inclination to oscillate around a value in the zone of high inclinations ($140^\circ > i > 40^\circ$) where the evolution is much faster. We have also performed an additional simulation that includes the perturbations of the four giant planets on the heliocentric orbit of the centre of mass of the binaries. The initial conditions for the heliocentric orbit of the centre of mass, for the mutual orbit and for the orbit of Neptune, was exactly the same as those used previously. As in the previous simulations, we have used EVORB in barycentric coordinate (Fernández et al. 2002), and an integration step of 0.1 yr, which guarantees adequate precision. The mutual perturbations between the planets were included in the numerical integration. In this case, due to the high computational cost of the simulations and also because our main purpose here is to

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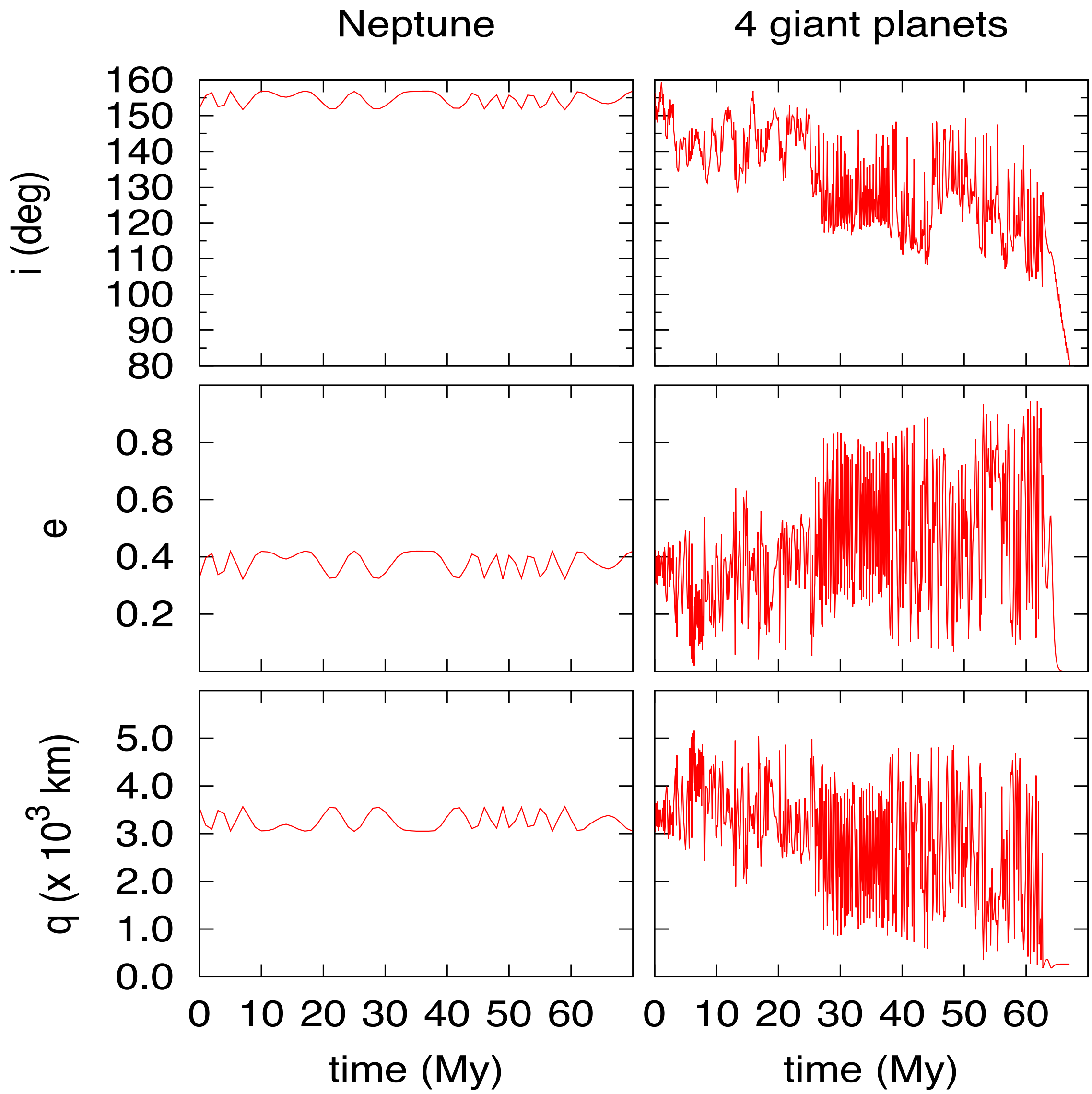

Figure 5. In the top panels, the evolution of the mutual inclination of the binary is shown with only Neptune as the disturbing planet and with the four giant planets. The middle panels show the same but for the mutual inclination and the bottom panels depict the evolution of the pericentre distance. The short periodic variations due to the presence of the other three giant planets cause a much more irregular orbital evolution. Tidal friction is included in the model.

observe whether it would be justified or not to include the other three giant planets in a numerical simulation of the dynamical evolution of TNBs, we have restricted the total time span of the simulations to 10^9 yr.

The periods of the oscillations of the orbital inclination and of the longitude of the ascending node of the heliocentric orbits are noticeably smaller when the four giant planets are included in the model, than when only Neptune is included in it. In general, we have found that in ∼20 per cent of the cases, the evolution of the mutual orbits that include the four giant planets presents noticeable variations in relation to the ones where only Neptune is considered. A typical case is the one shown in Fig. 5.

5 CONCLUSIONS

In this work, we have carried out a study of the influence of planetary perturbations on the dynamics of TNB objects. We focus on how the changes of the heliocentric orbit of the centre of mass due to these perturbations affect the characteristics of the Kozai cycles. This is so because the orientation of the mutual orbit with respect to the heliocentric one plays a fundamental role, both in the magnitude and in the characteristic of these cycles. We found that in a non-negligible fraction of cases (∼25 per cent), this effect produces substantial changes in the dynamical evolution of TNBs. The small oscillations of the orbital inclination and the precession of the heliocentric orbit, although they generally have longer periods than the characteristic Kozai times, induce variations that make the dynamical evolution of TNBs irregular. When these variations are coupled to the evolution due to tidal friction, substantial changes are produced in the lifetime of these objects. We have found cases where the lifetime increases and others where it decreases, in both cases substantially. A detailed study of the general problem of a binary minor planet disturbed by giant planets, which would be of interest both in the Solar system and in extrasolar planetary systems, is beyond the scope of this work. It

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is a problem with a huge amount of free parameters. In this case, we have only analysed the situation of binary objects of the classical hot population of trans-Neptunian space. It is clear after the results we have found that the effect of giant planets cannot be neglected when modelling their evolution. Nevertheless, from a statistical point of view, there is not much difference in the final states of the TNBs that we have studied. An object with a given initial condition ends up with the same end state whether planets are included or not. In addition, the final distributions of the orbital elements (a, e, and i) are very similar and for this reason we do not show them here. This effect, however, could have important consequences for the evolution of binary populations in other planetary systems, but this analysis is outside the scope of this paper.

DATA AVAILABILITY

The data underlying this article will be shared on reasonable request to the corresponding author.

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