On the dynamical evolution and end states of binary centaurs

A. Brunini[1,2,3]★

[1]*Grupo de Ciencias Planetarias*
[2]*Facultad de Ciencias Astronómicas y Geofísicas UNLP, IALP–CCT La Plata, CONICET*
[3]*Paseo del Bosque s/n 1900, La Plata, Argentina*

ABSTRACT

In this paper, we perform a numerical integration of 666 fictitious binary Centaurs coming from the trans Neptunian space. Our population is restricted to tight binaries whose components have sizes between 30 and 100 km. We included the dynamical perturbations from the giant planets, Kozai Cycles induced by the Sun and tidal friction on the orbits of the binaries. We found that most binaries are disrupted during one of the close planetary encounters, making the mean lifetime of binary Centaurs much shorter than the one of single Centaurs. Nearly 10 per cent of the binaries reach a very tight circular orbit, arguing in favour of the existence of a non-negligible population of contact Centaurs. Another 10 per cent survive as a binary during their lifetime as Centaur. Our simulations favour the existence of a small population of very tight binary Centaurs.

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

1 INTRODUCTION

There is increasing observational evidence suggesting that binary trans Neptunian objects (TNOs; hereafter TNBs or trans Neptunian binaries) are common (Parker 2012; Stansberry et al. 2012). At present, we count 79 binary or multiple TNOs in the sample of known objects between 30 and 70 au, representing almost 5 per cent of the whole observed sample (Stephens & Noll 2006).

Most known TNB systems have a separation of less than 2 per cent of the Hill radius, which is defined as

$$R_H = a_\odot (1 - e_\odot) \left(\frac{M_{bin}}{3 M_\odot} \right)^{1/3}, \qquad (1)$$

where $a_\odot$ and $e_\odot$ are the semimajor axis and eccentricity of the heliocentric orbit, respectively, $M_{bin} = M_{prim} + M_{sec}$ is the combined mass of the binary components (primary and secondary component respectively) and $M_\odot$ is the mass of the Sun. The components of the TNBs discovered so far exhibit small difference of brightness, which is in favour of systems of near-equal mass ratio. Despite easier to detect, there is only a very small fraction of TNBs in wide orbits (separated by more than 10 per cent the Hill radius).

Up to the present, different mechanisms have been proposed to create TNBs. Nesvorný, Youdin & Richardson (2010) have shown that binaries may be formed by gravitational collapse in which the excess of angular momentum prevents the formation of a single object. The TNBs formed in this way have preferentially near-equal mass ratios, but moderately eccentric orbits, in contradiction with the observed population. Dynamical captures can also produce

TNBs (e.g. Goldreich, Lithwick & Sari 2002; Lee, Astakhov & Farrelly 2007) of near-equal mass ratios but on wide and eccentric orbits. Binary formation through massive impacts leads to very unequal binary mass ratios that are much different to those actually observed (Noll et al. 2008). Funato et al. (2004) proposed a small impact combined with dynamical capture in order to create TNBs, but this mechanism only produces very high eccentricities. It is clear that none of the proposed formation mechanisms can explain the characteristics of the observed population of TNBs. Nevertheless, it is important to note that post formation orbital evolution of TNBs can largely erase their primordial properties.

As it was recently shown (Porter & Grundy 2012), tidal friction combined with solar perturbations, acting on the age of the Solar system, strongly affect the orbital properties of TNBs, and therefore, their present orbits are not necessarily primordial.

As the scattered disc is the main source of Centaurs, it is thus natural to think that there should be a population of binary Centaurs (BC). In fact, two binary systems were found in the population of 201 known Centaurs to date: 42355 Typhon-Echidna (Noll et al. 2006) and 65489 Ceto-Phorcys (Grundy et al. 2007). Their main properties are summarized in Table 1.

There is no universally accepted definition of a Centaur. Nevertheless, it is generally accepted that they are objects that are entering the planetary region from the trans Neptunian region, evolving to the Jupiter family comets zone (Fernández 1980; Levison & Duncan 1997; Duncan, Levison & Lee 1998). Therefore, Centaurs have a transitory and transfer nature, whose dynamical behaviour is dominated by random and frequent close encounters with the giant planets.

In this paper, we will use the same definition of Centaurs as adopted in Di Sisto & Brunini (2007, hereafter DSB07), as those

★E-mail: abrunini@fcaglp.unlp.edu.ar

Table 1. Main orbital and physical properties of the known BC. Their Hill radii were computed assuming the object in the perihelion and a density of 1 g cm^{-3}.

Object	a_{bin} [R_H]	e_{bin}	R_{prim}/R_{sec}
Typhon/Echidna	0.002	0.526	1.8
Ceto/Phorcys	0.006	<0.015	1.3

objects with $5.2 < q < 30$. DSB07 have performed a numerical integration of 1000 particles (95 real SDOs and 905 clones of them), under the gravitational influence of the Sun and the four giant planets. These particles started their evolution as scattered disc objects. The simulation was carried out with the hybrid quasi-simplectic integrator EVORB (Fernández, Gallardo & Brunini 2002) following the evolution of each particle for 4.5 Gyr or until it is ejected from the Solar system in hyperbolic orbit, collides with a planet, reaches a semimajor axis $a > 1000$ au or enters the region inside of Jupiter orbit ($r < 5.2$ au), where it is under its gravitational control, being able to go over a Jupiter family comet.

Regarding the Centaur population, the relevant result for our present purpose is that 666 of those particles become a Centaur during some period of the simulation, being their mean lifetime as Centaur 72 Myr. The total number of close encounters (encounters at a distance less than 3 Hill radii of the planet) with the giant planets was 1301 937. All the 666 particles encounter Neptune, representing 78.22 per cent of the total number of encounters, 488 particles encounter Uranus, with 18.32 per cent of the encounters, 380 particles encounter Saturn, having 3.4 per cent of the encounters and 142 particles encounter Jupiter, representing 0.06 per cent of the encounters.

Regarding to the existence of a population of BCs, and as the dynamics of Centaurs is dominated by close encounters with the giant planets, the question we are formulating is if a fraction of TNBs could survive this dynamical challenge through the Centaur region. As a first attempt to answer this question, we perform a numerical simulation of a synthetic population of BCs, considering the most important effects: solar and planetary perturbations, and tidal friction. In the next section, we describe the model and the initial conditions. In Section 3, we show the main results. The last section is devoted to the conclusions.

2 NUMERICAL MODEL AND INITIAL CONDITIONS

2.1 Numerical procedure

In our previous Centaur simulation (DSB07), we recorded the orbital parameters of the Centaurs and the giant planets at intervals of 10^3 yr, and also the information to reconstruct each close encounter (time, position and relative velocity at the beginning of each close encounter, when the particle is at 3 Hill radii from the planet). We identify each one of these 666 particles in the DSB07 simulation with the centre of mass of a Centaur binary. Once the orbit of the binary around this centre of mass is defined (see below), at the beginning of the simulation, each close encounter can be integrated in the planetocentric frame. To do this, we used a Bullirsh and Stoer integration routine, which is the same as used in our integration package EVORB (Fernández et al. 2002). During close encounters between a BC and a planet, the perturbation by the Sun on the binary was included, assuming for the planet an elliptic heliocentric orbit, whose Keplerian elements were taken from DSB07 simulation, at the near-
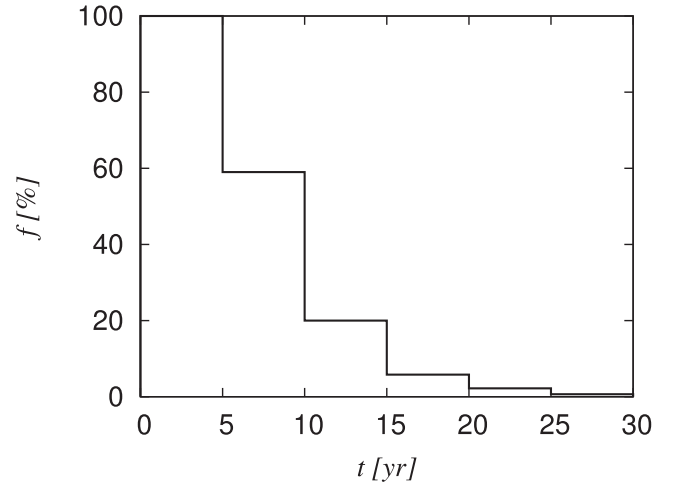

Figure 1. Cumulative distribution of the duration of the close encounters with the giant planets. 90 per cent of close encounters are shorter than 15 yr.

est time corresponding to this close encounter. As the duration of the close encounters in the simulation is always ≤ 30 yr, considering an elliptical orbit for the giant planets is a good approximation. Fig. 1 shows a histogram of the cumulative fraction of encounter versus their duration in DSB07/simulation. We observe that more than 90 per cent of the close encounters are shorter than 15 yr. As a check, we have integrated a sample of 100 binary encounters with a full model, including the four giant planets. Significant differences with the orbits of the binaries at the end of the encounters with respect to the cases when the planetary perturbations are discarded were not found. Therefore, during the encounters, the perturbations from the rest of the planets were not included.

Between successive close encounters, we compute the evolution of the orbit of the binary by means of the secular Hamiltonian theory of Fabrycky & Tremaine (2007) that accounts for Kozai cycles induced by the solar perturbation. The secular theory can be applied in this case because the angular momentum of the heliocentric orbit is much larger than the one of the CB.

The inclusion of Kozai cycles is crucial to properly account for tidal friction, because its effect is strongly dependent of the closest approach between the components of the binary. Kozai cycles affect the binary orbital eccentricity at an inclination in such a way that the quantity

$$L_z = \sqrt{\left(1 - e_{bin}^2\right)} \cos i \qquad (2)$$

is conserved. In the secular theory, there are also other two conserved quantities: the binary semimajor axis a_{bin} and

$$H' = -2 - 3e_{bin}^2 + \left(3 + 12e_{bin}^2 - 15e_{bin}^2 \cos^2 \omega_{bin}\right) \sin^2 i, \qquad (3)$$

where ω_{bin} is the angle of pericentre of the binary orbit and i is the inclination of the binary orbital plane with respect to the plane of the heliocentric orbit. Using these relationships, Kozai (1962) proved that a binary can reach a maximum eccentricity given by

$$e_{max} = \left\{ \left(8 - 12L_z^2 - H' \right. \right.$$
$$\left. \left. + \left[\left(10 + 12L_z^2 - H'\right)^2 - 540L_z^2\right]^{1/2} \right) \Big/ 18 \right\}^{1/2} \qquad (4)$$

that could be very large depending on the initial orbital inclination, even if the initial orbit is nearly circular. In such circumstances, the
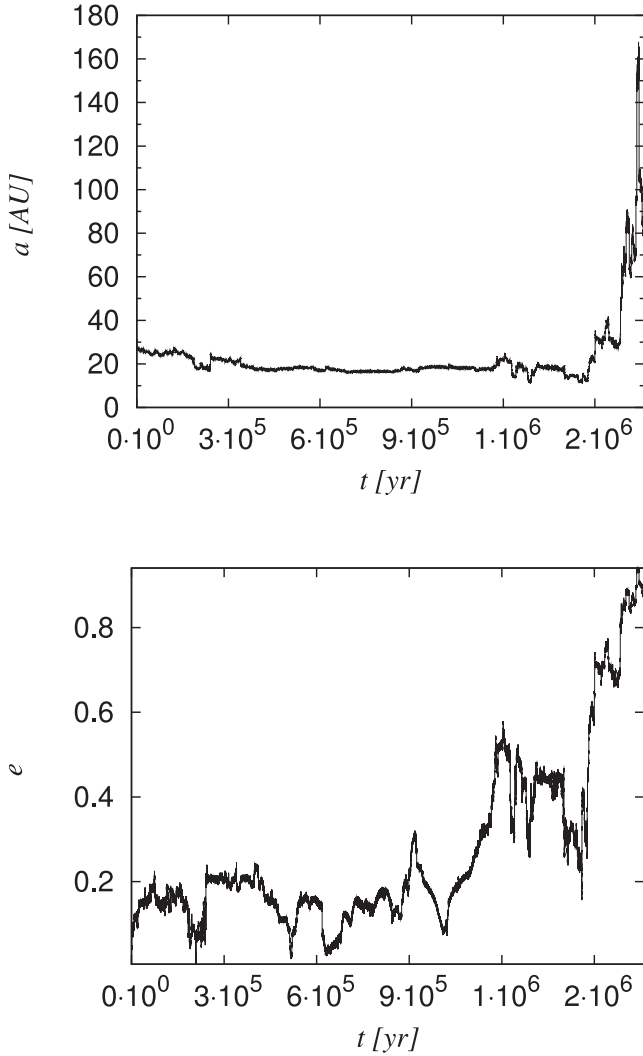
Figure 2. Top: evolution of the semimajor axis of a typical Centaur. Bottom: evolution of the eccentricity of the same Centaur.

Figure 3. Evolution of the quantity d showing that the heliocentric orbit of the binary may be interpolated from DSB07.

pericentric distance may reach very small values, where the effect of tidal friction is strong (Porter & Grundy 2012).

As under adequate conditions, the circularizing effect of mutual tides could compensate the orbital excitation due to planetary close encounters, it is thus important to accurately model tidal friction.

In order to apply the secular theory, the heliocentric orbit of the binary centre of mass was taken from DSB07 simulation records. As we have records at intervals of 1000 yr, the orbital elements for the exact time we need in the present simulation were obtained by a linear interpolation. To prove that this procedure is good, we have taken 10 of the 666 Centaurs and repeated the numerical integration of their dynamical evolution, recording a, e and i at intervals of 1 yr.

In Fig. 2, we show the evolution of the semimajor axis and the orbital eccentricity for one of these 10 centaurs that suffer more than 300 close encounters with the giant planets. This is a representative case. After that, we pick up values of these orbital elements each 1000 yr. From these elements, we computed numerical values a_{int}, e_{int} and i_{int} each 1 yr by linear interpolation, and the quantity

$$d = \sqrt{[(a - a_{int})/a]^2 + [(e - e_{int})/e]^2 + [(i - i_{int})/i]^2} \quad (5)$$

was computed, except for those values recorded during close encounters.

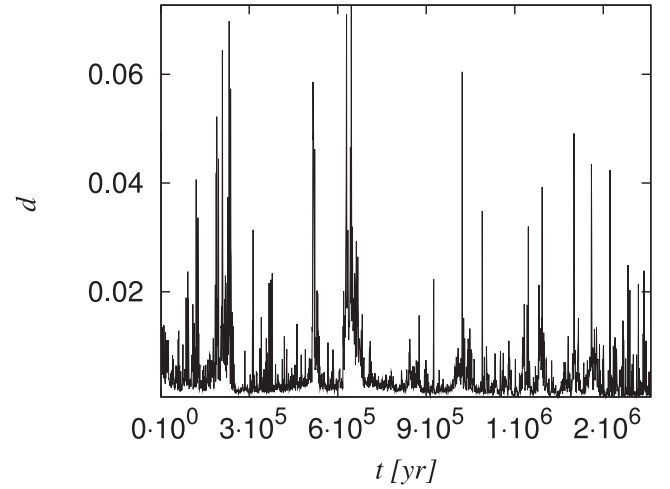In Fig. 3 we show the quantity d for the Centaur shown in Fig. 2 that allows us to observe that the interpolated value never departs from the actual value in more than 10 per cent. The same behaviour was found in the 10 explored cases.

For the tidal friction model, we used the same prescription as Fabrycky & Tremaine (2007) and Eggleton & Kiseleva-Eggleton (2002).

2.2 Initial conditions

For the tidal model, we have to adopt Q, the tidal dissipation function of the binary members and K_L which is the second tidal Love number. We used the same definitions as in Porter & Grundy (2012) for them: for most cases, we adopt the canonical values for icy homogeneous solid bodies of $Q = 100$, density $\rho = 1\,\mathrm{g\,cm^{-3}}$ and

$$K_L = \frac{3}{2}\left(1 + \frac{19\mu_r r}{2\,G M_{bin}\rho}\right), \quad (6)$$

with the rigidity $\mu_r = 4 \times 10^9\,\mathrm{N\,m^{-2}}$. For one simulation, we assumed that the binary is composed by two rubble piles, with $\rho = 0.5\,\mathrm{g\,cm^{-3}}$,

$$K_L = r/10^5\,\mathrm{km}. \quad (7)$$

and $Q = 10$.

We start all the simulations with separations of the binary components at random between 2 and 10 per cent of their Hill radii. Wide binaries are more prone to be disrupted during close encounter with the planets (Parker & Kavelaars 2010) and were not considered in this work. In fact, we will show that the most common end state of BC is separation of the components. The inclination of the orbital planes were also taken at random between $-90°$ and $90°$. e_{bin} was also taken at random between 0 and 0.9.

The 666 binaries in the simulations have radii at random in the range $30 \leq r \leq 100$ km, generated with a power-law size distribution with exponent $q = -3.5$ (Bernstein et al. 2004), appropriate for TNOs in this size range. Two sets of simulations were done. One with components of equal radii (set ER) and a second one with components of different radii (set DR). For each ER simulation, we have generated 666 radii at random with the desired size distribution function; thus, assigning the same radius to both components of each one of the 666 system. For the DR cases, the radius of each

component was generated at random with the above-mentioned size-distribution function. For each one of the sets, we performed two simulations. One in which the objects are in synchronous rotation (S). For these cases the spin vectors of both components are assumed to be perpendicular to the orbital plane and in the same direction of the orbital angular momentum of the binary system. In addition, both components have the same spin period, which is equal to the orbital period of the binary. This rotational state is the one called 'fully synchronous orbit' by Taylor & Margot (2011). For these cases, we also adopt random orbital eccentricities rather than circular orbits, because we assume that the orbit of a binary is easily affected by close encounters with the planets, but their diurnal rotation does not.

In the other set of runs, the spin period is taken at random (R) in the interval $2\,h \leq$ spin period $\leq 48\,h$. In these cases, each component has its own diurnal rotation rate. Also in this case, the orientation of the spin axes was at random.

The possible end states we considered are

(i) survival during all the lifetime as a Centaur,

(ii) separation of the components, either because the orbit becomes hyperbolic after a close encounter or the apocentric distance becomes larger than the Hill radius,

(iii) collision between the components, when the pericentric distance becomes shorter than the mutual Roche radius,

(iv) collision of one component with a planet.

The last option was not found in any case. Also, we did not find the production of a planetary satellite, although short temporary captures of both components were found in very few cases (Brunini 1996).

For the third option, we differentiate the case when the objects reach the Roche distance with very small eccentricity ($e_{bin} \leq 10^{-3}$). In this case, they could contact each other at very small relative velocity, and a contact binary could form. We do not claim that a contact binary is formed in this way. It is a problem to be investigated in the future, and several outcomes could be possible. Nevertheless, as far as we know, this is the natural mechanism to form contact binaries.

We want to remark that we do not intend to give a complete description of the CB population, but only a contribution to a better understanding of the dynamical response of this particular population binaries coming from the scattered disc, when they become a CB.

3 RESULTS

As it was already mentioned, collisions on to a planet were not found in our simulations. Most binaries end up being disrupted. In most cases, during one of the close encounters with a giant planet. There are events that inject enough orbital energy to the system in such a way that the binary orbit becomes hyperbolic, but in several cases, the semimajor axis and the eccentricity experience a random walk, and during the last encounter, the semimajor axis increases in such a way that the apocentric distance becomes larger than the binary Hill radius.

In few cases, the eccentricity grows up gradually and the pericentre is reduced making the binary components to collide with each other. These collisions are at a high relative velocity, and then the most probable outcome is disruption of the components in fragments. Nevertheless, this end state is the most rare. In Table 1, we show the statistics of the end states for the different runs. We observe several relevant features. The difference in the number of

BCs that survive, or are disrupted, is not too significant. Some differences are in the fraction that reach the state we call *potential contact binary*. For the case of non-synchronized rotation, the rate of change could be either negative or positive, depending on the spin rate and the orbital motion. Whether the satellite orbit is direct or not also affects the sign of the semimajor axis variation (Hut 1982; Murray & Dermott 1999). In the case of a binary system where the objects have equal values of the frictional time-scale, orbital eccentricity $e_{bin} \gg 0$ and synchronized rotation, the rate of change for the semimajor axis can be approximated as (Porter & Grundy 2012)

$$\frac{da_{bin}}{dt} \propto -\frac{a_{bin}}{(1-e_{bin})^{15/2}}, \qquad (8)$$

and it is always negative. Therefore, we could expect nearly twice the number of binaries reaching this end state for the case of synchronized rotation as compared to the case of random rotation.

On another hand, the differences observed between the cases of equal and unequal radii are not clear and could be attributed, in principle, to statistical fluctuations of a small sample.

The factor Q also plays a role in this case because circularization by tidal friction is faster than in the case with $Q = 100$, a result already found by Porter & Grundy (2012). In the three cases, the effect of tidal friction is evident. In few cases, the *potential contact binary* is reached very soon. A fraction of our binary population has initial orbital and physical configurations that produce a fast tidal evolution, and therefore we should consider this cases as binaries that becomes Centaurs already as *potential contact binary*. Our initial conditions are not representative of these classes of objects because we are discarding the tidal evolution while the object is in the trans Neptunian space. One of such cases is shown in Fig. 4.

In some cases the *potential contact binary* end state is achieved after a close encounter that affects the pericentric distance and starts the action of tidal friction, as it is the case shown in Fig. 5.

Regarding the ~10 per cent that survive not being *potential contact binaries*, it is worth noting that in DSB07 and so in this simulation, the evolution ends up when the Centaurs reach a Jupiter crossing orbit. Therefore, close encounters with Jupiter are underestimated, being these events surely the most catastrophic ones for the survival of the binaries. In addition, the fact that they survive does not ensure that the binary, as a Centaur, can reach Jupiter's orbit.

Fig. 6 depicts the distribution of lifetime of our binaries as Centaurs for one of our simulations (ER S, see Table 2). The mean lifetime of our population is shorter than the mean lifetime of 72 Myr reported by DSB07 for Centaurs and much shorter than the 4.5 Gyr of the simulation of Porter & Grundy (2012). For this reason, we do not observe in our results a significant trend in the final configurations of the survivors. We have to observe that the distribution shown in Fig. 6 underestimates the binary lifetime, because for those binaries that achieve the potential contact state the simulation stops.

4 CONCLUSIONS

In this paper, we have performed a numerical simulation of the dynamical evolution of 666 BC under the influence of the giant planets and considering mutual tidal interaction.

We observe ~7 to ~14 per cent of BCs reaching an end state with very low orbital eccentricity and a tight orbit. The end state is not strongly dependent on the initial orbital, physical and rotational properties of the binary. Therefore, although we have to be cautious
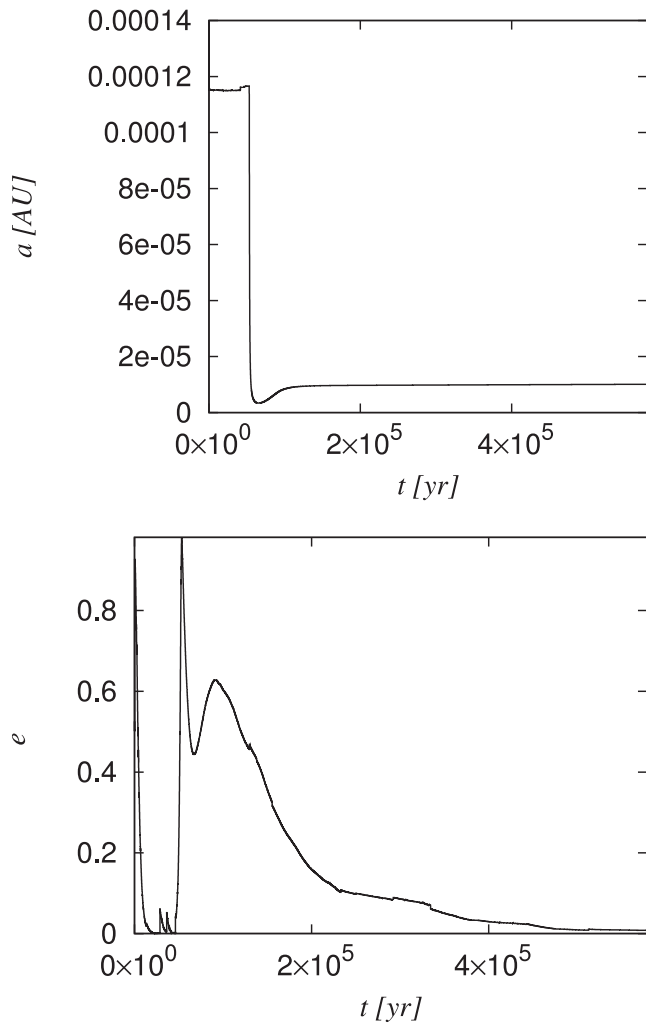
Figure 4. Top: evolution of the semimajor axis of a BC whose initial conditions make it strongly affected by tides. Bottom: evolution of the eccentricity of the same BC.

with this assertion, our results suggest that during the journey as a Centaur, a non-negligible fraction of TNBs could become contact binaries, and therefore, contact binary Jupiter family comets could exist, because they could resist encounters with Jupiter. This is an interesting question to be investigated in the future.

Our simulations have a number of limitations, like the absence of shape effects. As it was already shown by Porter & Grundy (2012), oblateness of the binary components lowers the effectiveness of Kozay Cycles, thus making some systems to remain in highly eccentric orbits. This could enlarge the fraction of disrupted systems. Also, it may have a major effect on the rotational evolution of the binaries, although on a much longer time-scale than their mean lifetime as Centaurs. Nevertheless, accurate modelling of this effect is complex, because small objects with known shapes are not pure oblate spheroids (Porter & Grundy 2012).

Also, we have explored a very limited parameter space. The tidal parameters, such as the factor Q, do not seem to have a major influence on the final statistics (likely, a factor of 2 in the number of contact binaries), due to the relatively short mean lifetime of the Centaur population. The major limitation is in our initial conditions. They are not self-consistent, in the sense that we neglect the previous evolution in the trans Neptunian space. Therefore, we should have a
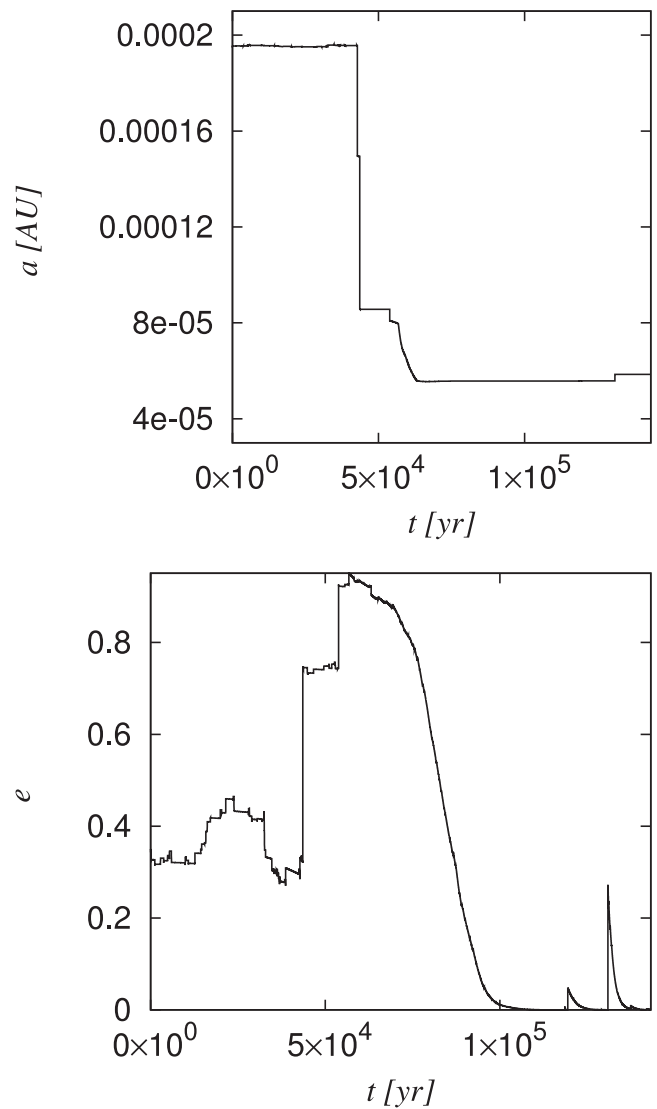

Figure 5. Top: evolution of the semimajor axis of a BC that after experiencing a stage of strong close encounters enters in a regime where tides sculpt its final orbit. Bottom: evolution of the eccentricity of the same BC.
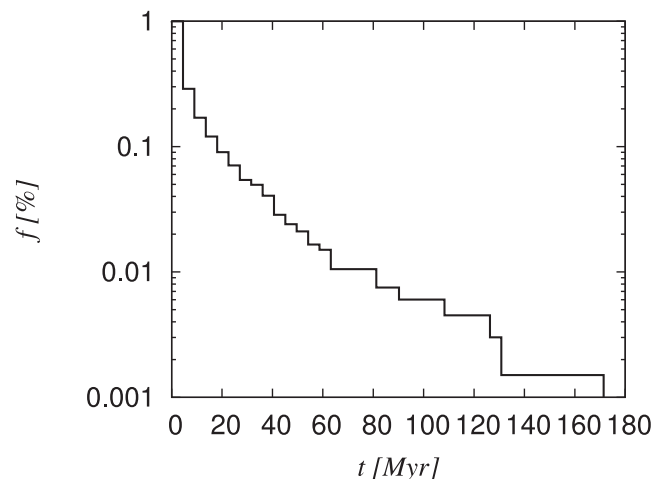

Figure 6. Distribution of the lifetime of our objects as BC. Very few binaries live more than 1 Myr.

Table 2. Statistics of the runs. ER: equal radii. DR: non-equal radii. S: synchronous rotation. R: random rotation.

RUN	SURV.	CONTACT	COLL.	SEP.
ER S $Q = 100$	49	91	0	526
DR S $Q = 100$	53	74	1	538
ER R $Q = 100$	51	46	4	565
DR R $Q = 100$	56	49	1	560
DR R $Q = 10$	60	68	1	537

number of binaries entering in the Centaur region already as contact binaries that could survive the entire simulation. On another hand, we are not able to follow the orbital evolution once reached the contact binary state.

All these limitations preclude us to give estimations of the possible population of BCs nor characterize it. We are planning to extend our simulations to take into account these limitations, and following the simulation within Jupiter's orbit, in order to have a better answer to our initial questions.

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