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Dynamical capture in the Pluto-Charon system

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Abstract This paper explores the possibility that the progenitors of the small satellites of Pluto got captured in the Pluto-Charon system from the massive heliocentric planetesimal disk in which Pluto was originally embedded into. We find that, if the dynamical excitation of the disk is small, temporary capture in the Pluto-Charon system can occur with non-negligible probability, due to the dynamical perturbations exerted by the binary nature of the Pluto-Charon pair. However, the captured objects remain on very elliptic orbits and the typical capture time is only $\sim$ 100 years. In order to explain the origin of the small satellites of Pluto, we conjecture that some of these objects got disrupted during their Pluto-bound phase by a collision with a planetesimal of the disk. This could have generated a debris disk, which damped under internal collisional evolution, until turning itself into an accretional disk that could form small satellites on circular orbits, co-planar with Charon. Unfortunately, we find that objects large enough to carry a sufficient amount of mass to generate the small satellites of Pluto have collisional lifetimes orders of magnitude longer than the capture time. Thus, this scenario cannot explain the origin of the small satellites of Pluto, which remains elusive.

Keywords Planetary systems · Natural Satellites · Numerical Methods
Numerical integration

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1 Introduction

The Pluto-Charon-Nix-Hydra system is in the Kuiper Belt, a disk of numerous objects spanning the region beyond Neptune's orbit up to ∼50 AU. Charon, the largest satellite, has a radius about half of Pluto's radius, which implies that the center of mass of the Pluto-Charon system is outside Pluto. The outer satellites Nix and Hydra, discovered in 2005 (Weaver et al, 2006), are much smaller than Charon and they orbit the center of mass on nearly circular orbits, in the orbital plane of Charon.

The four-body orbital solution of Tholen et al (2008) determined accurate masses of Charon, Nix and Hydra. The best-fit Charon/Pluto mass ratio is 0.1166, which implies that Charon's mass is 1.52 $\times 10^{21}$ kg. The estimated masses of Nix and Hydra are 5.8×10^{17} kg and 3.2×10^{17} kg, respectively. The diameters of both small satellites were estimated by assuming that they have a Charon-like density (1.63 g cm^{-3}). This gives diameters of 88 km and 72 km for Nix and Hydra, respectively.

The location of Nix suggests that it is near the 4:1 mean motion resonance with Charon, while Hydra is near the 6:1 resonance (Weaver et al, 2006; Buie et al, 2006). However, the investigation of several different resonant arguments showed that Nix and Hydra are not in 4:1 and 6:1 resonances with Charon, respectively, at present (Tholen et al, 2008). Any model that aims at explaining the origin of Nix and Hydra should explain how these bodies ended up in their near-resonant orbits with small eccentricities and small inclinations related to Charon's orbital plane.

The formation of Pluto-Charon pair through a giant impact (McKinnon, 1989; Canup, 2005) is widely accepted. In the past few years, the origin of Nix and Hydra has been debated in the literature. Stern et al (2006), Ward and Canup (2006) and Canup (2011) advocated a scenario in which the origin of Charon, Nix and Hydra is credited to the same event, i.e. as the result of a large collision of an ancient body on Pluto. The collision left Charon, the remnant of the projectile, on an orbit with a semi major axis equal to a few Pluto radii (Canup, 2005), and generated a debris disk just beyond Charon's orbit (Canup, 2011). The disk was not radially extended enough to account for the currently large orbital radii of the satellites Nix (43 radius of Pluto, R_p) and Hydra (57 R_p) (see Figure 6 Canup, 2011). However, Charon migrated by tidal interaction to its actual position at ∼17 R_p. In this process, it was proposed that Nix and Hydra got captured in the 4:1 and 6:1 mean motion resonances with Charon and then they were transported outwards as these resonances migrated together with Charon.

It remains to be shown, however, whether resonant migration can efficiently transport Nix and Hydra. Migration in a mean motion resonance typically raises the eccentricities of the resonant particle, while the current orbits of Nix and Hydra are basically circular. To overcome this problem, Ward and Canup (2006) proposed that Nix and Hydra got captured in the 4:1 and 6:1 co-rotation resonances with an eccentric Charon. In fact, co-rotation resonances do not excite the particles eccentricities during the outward migration.

However, the set of parameters that allows capture in the 4:1 co-rotation resonance and the one that allows capture in the 6:1 resonance have an empty intersection: so, the Ward and Canup mechanism could not have worked for Nix and Hydra simultaneously (Lithwick and Wu, 2008). Also, the transport of Nix and Hydra's orbits by resonant migration is ruled out by extensive numerical simulations of tidal models of Charon's migration (e.g. Peale et al, 2011; Cheng, 2011); most of the resonant particles are not stable and are eventually scattered by Charon and removed. When the hydrostatic value J_2 of Pluto is taken into account, disk particles can not be transported in resonance while preserving near circular orbits and all the test particles are eventually ejected.

In the last year another small satellite was discovered orbiting Pluto between the orbits of Nix and Hydra. This "new" body, temporarily named P4, has a diameter estimated between 13 to 34 km. This satellite was discovered during a search for faint dust rings; however, no such ring was discovered[1]. During the preparation of this manuscript a fifth moon was found orbiting Pluto[2], hereafter P5.

In this paper, we consider a potential alternative scenario for the origin of the minor satellites of Pluto and their peculiar orbits. We briefly explain here the general idea.

In the early phases of the Solar System, the Pluto-Charon binary was embedded in a massive disk of planetesimals, probably 1,000 times more populated than the current Kuiper Belt (see Morbidelli et al, 2008, for a review). This massive disk might have survived for hundreds of millions of years, before being strongly depleted by the orbital evolution of the giant planets (Levison et al, 2008). During the massive disk phase, numerous planetesimals should have had close encounters with the Pluto-Charon binary. If Pluto had been a single object, all encounters would have been hyperbolic fly-bys. However, the existence of Charon opens the possibility of three-body (even four-body, including the effect of the Sun) energy exchanges, leading to the capture of the incoming planetesimal on a bound orbit around Pluto. The captured orbits are expected to have large eccentricities and all captures are expected to be temporary, because energy exchanges are reversible. However, if the captured planetesimal(s) had been broken by collisions with other incoming objects during their capture-phase, then the disk of debris generated by the breakup could have behaved in a dissipative way, damping the debris eccentricities and inclinations by mutual collisions. Eventually a debris disk co-planar with Charon and with circular orbits could have formed, leading subsequently to the formation of small satellites such as Nix, Hydra and P4,5.

The plausibility of this idea needs to be investigated on quantitative grounds. Thus, in section 2, we compute the probability that planetesimals encountered the Pluto-Charon binary during the massive-disk phase as well as the orientations and mutual velocities of their incoming orbits. We then explain how we

[1] For the information regarding the discovery of P4, visit: http://hubblesite.org/newscenter/archive/releases/2011/23/

[2] The discovery of the latest moon is reported in http://hubblesite.org/newscenter/archive/releases/solar%20system/2012/32/full/

use this information to set up capture simulations. In section 3 we discuss the results of these capture simulations and estimate the size of the largest planetesimals that should have experienced a temporary capture around Pluto. We then compute the collisional lifetimes of the captured planetesimals as a function of size and compare them with their dynamical lifetimes as Pluto-bound objects. Section 4 summarizes our conclusions.

2 Method

As we said in the introduction, we consider an early phase during which Pluto was embedded in a massive planetesimal disk. Because Pluto was one of the most massive objects in the disk, presumably its orbit had a small eccentricity and a small inclination relative to the mid-plane of the disk, as a consequence of dynamical friction (Wetherill and Stewart, 1993). So, we can assume for simplicity that both Pluto's eccentricity and inclination were null. It is not known where Pluto was before the events that depleted the primordial trans-Neptunian disk and formed the current Kuiper Belt (placing Pluto onto its current orbit). There is a consensus that it was much closer to the Sun than it is today (Malhotra, 1993; Levison et al, 2008). Without loss of generality, we assume that the orbit of Pluto had a semi-major axis of 20 AU.

The first step of our investigation is to compute the encounter probability, velocity and orientation of the disk's planetesimals relative to the Pluto-Charon binary. For this purpose, we assume that the eccentricities e of the disk's planetesimals were randomly distributed up to $e_{\max}$ (a free parameter, whose value is discussed in sect. 3), while the inclinations i spanned the interval (0–$i_{\max}$), with $i_{\max} = e_{\max}/2$. We also assume that the semi major axes a of the planetesimals were randomly distributed in the interval 18 to 22 AU. We generate in this way sets of a, e, i for the disk's planetesimals, until we find a number $M \sim 1200$ planetesimals crossing the assumed orbit of the Pluto-Charon binary.

For each of these planetesimals, we compute the intrinsic collision probability p (defined as the probability per target km^2, per year), the unperturbed relative velocity v and the orientation of the relative velocity vector (θ, ϕ). This is done using a Opik-like approach (Wetherill, 1967). The orientation angles (θ, ϕ) are defined in a reference frame where the x-axis is directed along the velocity vector of the Pluto-Charon binary relative to the Sun, while the y-axis is directed towards the Sun from the Pluto-Charon barycenter (Fig. 1). More precisely, θ is the angle defining the projection of the relative velocity vector on the x–y plane and ϕ gives the latitude of the relative velocity vector relative to that plane. In fact, there are 4 possible equi-probable encounter configurations, corresponding to the 4 possible combinations of the signs of θ and ϕ. For each planetesimal, we chose randomly these two signs, thus fixing the encounter geometry.

For each planetesimal, we then simulate the close encounter of the Pluto-Charon binary with a swarm of N particles, with N proportional to the value of

p for the considered planetesimal. We use $N = 1$ for the planetesimal with the smallest $p = 9.3 \times 10^{-21}\mathrm{km}^{-2}\ \mathrm{yr}^{-1}$. The particles are uniformly distributed on the b-plane (Valsecchi and Manara, 1997), all having the same velocity vector relative to the Pluto-Charon binary as the considered planetesimal. The b-plane is here defined as the plane orthogonal to the relative velocity vector, which is tangent to the Hill sphere of the Pluto-Charon binary (Fig. 1). On the b-plane we set a new coordinate frame. The center of the frame is the projection of the Pluto-Charon barycenter along the direction of the relative velocity vector.

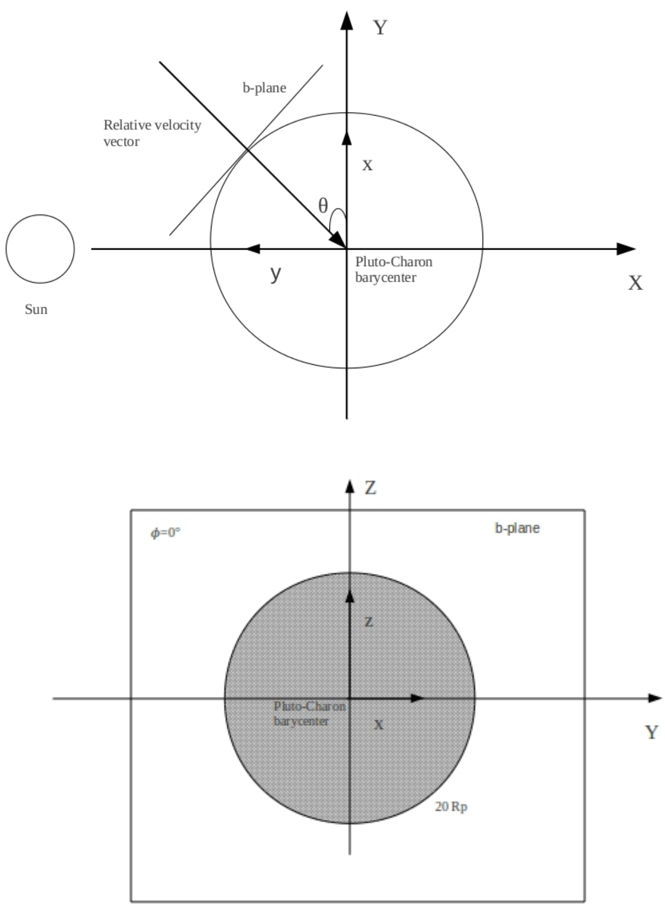

Fig. 1 From the top to bottom: view of the reference plane x-y and a representation of the b-plane when $\phi = 0°$. The line connecting the Sun, Pluto and Charon defines the X-axis.

Because the gravitational focusing of the Pluto-Charon system is small for the relative planetesimal velocities considered in this work (see sect. 3), the trajectories of the incoming particles are weakly curved. Thus, particles passing more than 20 Pluto radii away from the center of the frame on the b-plane have no chance to be deflected by encounters with Charon (which is at $\sim 15R_p$ from the Pluto-Charon barycenter). For this reason, we distribute the particles uniformly on the b-plane, but only up to $20R_p$ from the reference frame center.

For the particles that constitute the swarm associated to each planetesimal, the recipe described above sets the initial positions and velocities relative to the barycenter of the Pluto-Charon binary and the Sun. To start the integrations, we now need to fix the orbit and the position of Charon. We do this as follows. We assume that the inclination of the orbit of Charon around Pluto, measured relative to the orbital plane of the binary around the Sun, was the same as the current orbital inclination of Charon relative to the ecliptic plane 119° (Tholen and Buie, 1997). This is justified because, if the inclination of Pluto's orbit was impulsionally excited during the dispersion of the primordial trans-Neptunian disk and the formation of the current Kuiper Belt, the orientation of the orbital plane of Charon should have been preserved relative to an inertial frame. We then assume that the line of nodes of Charon orbit had a random orientation on the (x, y) plane. In addition, we assume Charon to have a random position along its circular orbit.

Finally, we apply a series of rotations and translations in order to transform the full system (Pluto, Charon, Sun and particles of the swarm) to a new reference frame, centered on Pluto, whose reference plane is the orbital plane of Charon. The integrations are performed in this new Pluto-centric frame, using the swift_rmvs3 integrator from the Swift package (Levison and Duncan, 1994). Each integration is continued until all swarm particles exceed a distance of two Hill radii (or 12,000 R_p) from Pluto (2 R_H hereafter). We call "temporarily trapped" the particles which have, at some time, a negative energy relative to the Pluto-Charon barycenter.

The probability P_i that a given planetesimal ($\#i$) is captured onto an orbit temporarily bound to the Pluto-Charon system is then computed as follows. Denote K_i the number of particles temporarily trapped out of the N_i particles integrated in its swarm, and denote by p_i the planetesimal's intrinsic collision probability. Then one has:

$$P_i = p_i (20R_p)^2 K_i / N_i \tag{1}$$

the probability P_i is expressed in yr^{-1}.

The mean probability of temporary trapping for the population of Pluto-crossing planetesimals in the disk is therefore

$$P = \sum_{i=1}^{M} (P_i / M). \tag{2}$$

where M is the number of planetesimals that we studied on Pluto-Charon-crossing orbits.

3 Results

3.1 Capture event

We started by assuming that the excitation of the disk can be characterized by $e_{\max} = 0.1$. This value comes from simulations of the self-excitation of the disk in the case where there are $\sim 1,000$ Pluto-size objects (Levison et al, 2009, 2011). In this case we find that the mean encounter velocity with the Pluto-Charon system, weighted over the intrinsic encounter probability p is 0.4 km s^{-1}.

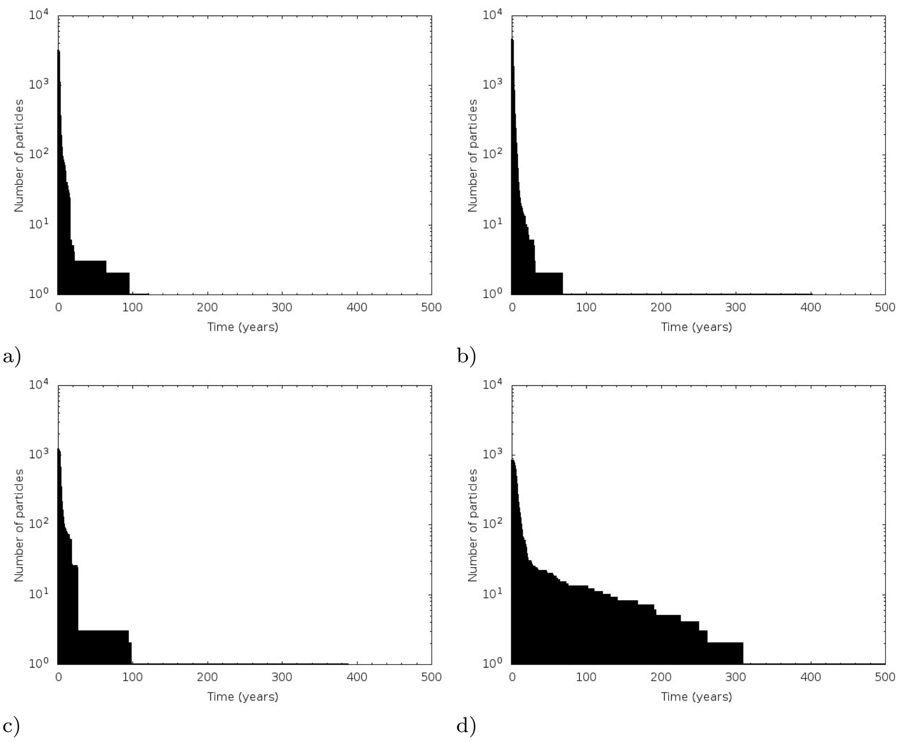

Fig. 2 The cumulative number of particles having a lifetime longer than a given value, for different assumed excitations of the planetesimal disk: $e_{max} = 0.1$ (a)), 0.07 (b)), 0.05 (c)) and 0.03 (d)).

With this characteristic incoming speed, the cumulative distribution of particle lifetimes is that shown in Fig. 2 a. Remember that the lifetime is measured here from the initial condition of a particle on the b-plane (approximately 1 R_H away from the Pluto-Charon barycenter) to the moment when the particle's distance from said barycenter exceeds $2R_H$. Notice that the cumulative distribution is made of two distinct features. There is initially sharp decay, due to the fact that most particles have lifetimes shorter than 20 years, followed by a "foot", due to a few particles with longer lifetimes, up to $\sim$ 100y. The particles with short lifetimes just have hyperbolic fly-bys with the Pluto-Charon system. The spread in lifetimes up to $\sim$ 20y is due to the spread in incoming velocities of the considered planetesimals. Instead, the "foot" is due to particles that experience temporary capture. In summary, more than a half of incoming particles have a lifetime shorter than 10 years. Only 1 particle remains bound to Pluto until 120 years, however this particle is very far from the planet, q (barycentric) reaches $600R_p$ during its orbital evolution. This is not very promising for our scenario.

Therefore, we considered disks with smaller dynamical excitation ($e_{\max} =$ 0.07 and 0.05). These disks correspond to weighted mean encounter velocities with the Pluto-Charon system of 0.3 km s^{-1} and 0.2 km s^{-1}. The resulting cumulative distributions of particle lifetimes (Fig. 2 b and c) do not change much relative to the previous case. The initial decay is a bit slower, because the incoming velocities are smaller. Again, particles with lifetimes longer than $\sim$ 20y experience temporary capture, and they are very few.

Finally, we decreased the eccentricity excitation of the disk to $e_{\max} = 0.03$. The distribution of cumulative lifetimes (Fig. 2 d) changes qualitatively relative to the previous cases. Now, many more particles experience temporary trapping (all those with lifetime longer than 22y), so that the "foot" of the distribution is well developed and we can appreciate the distribution of lifetimes within the "foot". The drastic increase in number of temporary captured particles is due to the fact that, with a weighted mean velocity at infinity of 0.1km/s, several particles have now a velocity lower than Pluto's velocity around the Pluto-Charon barycenter: 0.025km/s. Particles passing through the Pluto-Charon system typically experience a velocity change of this order and therefore, if their velocity at infinity is smaller, they are likely to be captured.

From this last sample, the orbital evolution, during the time range when the barycentric orbital elements are elliptic, of the long-lived particles (bound to Pluto for at least 100 years) are shown in the Fig. 3. The captured orbits cover a wide range of semimajor axis, eccentricity and inclination. Nevertheless, the pericentre varies from 30 to $\sim$ 1000 R_p. Eventually, collisions nearby Pluto could happen. In the next few years (>100 years) the orbital elements change significantly, and the particles escape in hyperbolic trajectories. As an isolated case, one particle remains trapped into elliptical orbit during the whole simulation (1000 years).

We now compute the temporary trapping probability expressed as a fraction of the Pluto-crossing population per year. This is done using (2). We find that P=1.1 $\times 10^{-13} y^{-1}$. Assuming that the massive planetesimal disk lasted about 500 My as in the Nice model (Gomes et al, 2005), then the probability that a Pluto-crossing particle experiences a temporary capture during the lifetime of the disk is 5.5×10^{-5}.

Using this information and a model for the size distribution of particles in the disk, we can now estimate the size of the largest planetesimal that should have experienced a capture event. Obviously, this is the diameter (D) for which the cumulative number of particles $N(> D) = 1/5.5 \times 10^{-5}$. As a

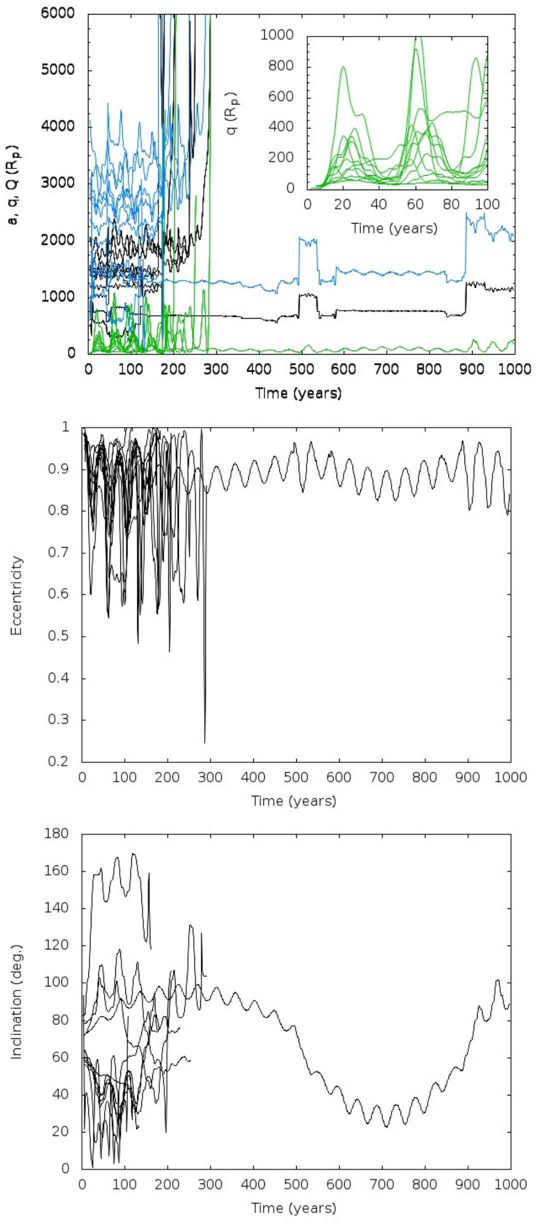

Fig. 3 Orbital evolution of particles captured by Pluto-Charon for at least 100 years. Top panel: blue lines represent the maximum plutocentric distances (Q), black lines represent the semimajor axis (a), and green lines represent the minimum plutocentric distances (q). Middle and bottom panel: evolution of the eccentricity and inclination, respectively.

disk model, we adopted that defined in Morbidelli et al (2009) (see Fig. 1a of that paper), which is consistent with all the constraints of the Nice model. The disk considered in Morbidelli et al, though, was spread in about 15 AU in radius. If we assume that $e_{\max}$ of the disk was 0.03, as to have a significant number of captures, one gets a mean eccentricity of $e_{\max}/2 = 0.015$ and only approximately 4% of such a disk would cross the orbit of Pluto. Therefore, the size of the largest temporarily captured planetesimal is the one such that $N(> D)/25 = 1/5.5 \times 10^{-5}$. We find $D = 300$km.

A body of this size carries a mass that is 25 times that of Nix and Hydra combined. Therefore, if this body were broken during its temporary capture phase, enough material would be liberated as a disk of debris around Pluto to allow, potentially, the formation of the small satellites observed today. Therefore, in the next section we compute the collisional lifetime of planetesimals in our adopted disk and compare it with the capture time.

Notice that, in principle, one should consider also the possibility that planetesimals are collisionally disrupted during hyperbolic fly-bys because, even if most fragments would escape from the Pluto-Charon system in that case, a fraction of them could be captured thanks to the wide distribution of the fragment ejection velocities. However, we checked that the cumulative time spent in hyperbolic fly-bys in all distributions of Fig. 2 is less than the cumulative lifetime of temporary captured particles in the distribution of Fig. 2 d. Thus, investigating the probability of disruption of temporary captured particles, as we do in the next section, is enough to test our model. In fact, if this probability turns out to be too small, the probability of collisional disruption during a hyperbolic fly-by would be even smaller.

3.2 Collisional disruption estimate

For a planetesimal with radius $R = 150$km, we assume that the value of the specific catastrophic disruption energy Q^* is the one given by Benz and Asphaug (1999) for competent ice and $v_{imp} = 0.5$ km s^{-1}. The mean impact velocity in our adopted disk is smaller than 0.5 km s^{-1}. Moreover, it is possible that primordial trans-neptunian objects were weaker than competent ice planetesimals by a factor of 4 (Leinhardt and Stewart, 2009). However, we are interested here in an order of magnitude estimate of the collisional lifetime to see whether our proposed scenario is plausible or not. Thus, we believe that the use of Benz & Asphaug is enough for our purposes at this stage.

In general, assuming equal bulk densities, the size of a projectile required to catastrophically disrupt a target is:

$$D_p = (2Q^*/v_{\rm imp}^2)^{1/3} D_t, \tag{3}$$

where D_p, D_t are the diameters of projectile and target, respectively, and $v_{\rm imp}$ is the impact speed.

In our case, $Q^* > 3 \times 10^8$ ergs g^{-1} and $v_{\rm imp} = 10^4$ cm s^{-1} (because captured particles are very eccentric –see Fig. 3– and spend most of the time near aphelion we neglect here the gravitational focusing of the Pluto-Charon system and the orbital motion of the target). Thus $(2Q^*/v_{\rm imp}^2) > 1$. This means that the target cannot be broken by anything smaller than its own size. It can only be broken if it smashes into something bigger, but this is out of the validity regime of the Benz and Asphaug formula (in fact, in this case the body would be a projectile, not a target). This means that, in a dynamically cold disk such as the one that we have been forced to assume to observe some temporary captures, collisions of $D = D_t$ bodies are accretional, for $D_t = 300$km.

The maximal size of bodies that can be collisionally broken in a collision with an equal-size body is the one such that $Q^*(D) = (1/2)v_{\rm imp}^2$. Using again Fig. 7 from Benz and Asphaug (1999), we find $D = 20$ km. According to Fig. 1 from (Morbidelli et al, 2009) these should be approximately 10^{10} objects of this size or larger in the disk, of which 2.2×10^4 would have experienced temporary capture in the Pluto-Charon system (as we said above, 4% of the particles would cross Pluto's orbit and 5.5×10^{-5} would be captured). Notice that this ensemble of bodies with $D = 20$ km contains $\sim$160 times the cumulative mass of Nix and Hydra, assuming equal densities.

We now estimate the collisional lifetime of D=20 km bodies. Using the Opik-like approach, we compute that the collision intrinsic probability, averaged over all crossing particles is $\bar{p} = 2.04 \times 10^{-19}$ km^{-2} y^{-1}. The probability of collisional break-up per year is therefore

$$P^* = \bar{p}[(D_p + D_t)/2]^2 N(> D_p) \tag{4}$$

where $N(> D_p)$ is the number of objects larger than D_p crossing the orbit of the target. For $D_t = D_p = D = 20$ km and $N(> D_p) = 4 \times 10^8$ (i.e. 4% of the total number of particles of this size in the disk) we find $P^* = 3.2\times10^{-8}$. This means that the collisional lifetime is 3.2×10^8 years, which is enormous relative to the temporary capture time of ~ 100 y.

In Morbidelli et al (2009), the cumulative size frequency distribution in the disk for $D < 100$km is $(N > D_p) \propto D^{-2}$. In Benz and Asphaug (1999) $Q^*(D) \propto D_t^\beta$ with $\beta = 1.25$. Moreover, from Eq. (3) one gets $D_p \propto (Q^*)^{1/3} D_t$ and the cross-section of the target is $\propto D_t^2$. Therefore, simple algebra shows that the collisional lifetime of an object of size D_T is proportional to $D_T^{(2/3)\beta}$. The total mass carried by the objects of this size temporarily captured in the Pluto-Charon system decreases as $1/D$. Thus, D cannot be smaller than D_{min}=20km/160=0.125km for which the collisional lifetime is $3.2 \times 10^8 \times (0.125/20)^{0.83} \simeq 5$My. Thus, the negative conclusion achieved for 20km objects is valid at any size.

Therefore we are forced to conclude that the collisional break-up of planetesimals temporary captured in the Pluto-Charon system cannot, by orders of magnitude, deliver enough mass in debris to allow for the subsequent formation of Nix and Hydra.

4 Conclusions

The origin of the small satellites of Pluto (Nix, Hydra and P4,5) is still elusive. In particular, their distant and quasi-circular orbits are difficult to explain in a scenario where these satellites are envisioned to be small debris generated in the Charon-forming collision (Lithwick and Wu, 2008; Peale et al, 2011; Cheng, 2011).

We have seen that planetesimals of the same size of the current known satellites, or even larger, could be captured in the Pluto-Charon system. However, the problem with purely capture mechanism is that it generally produces satellites in high eccentric and inclined orbits, which eventually escape in a few 100 years. To trap these objects permanently and produce satellites on quasi-circular and coplanar orbits like Nix and Hydra, we would need a strong damping mechanism. Unfortunately, tidal interactions with Pluto could not circularize Nix and Hydra's orbits even in a timescale as long as the age of the solar system (Stern et al, 2006). Thus, we miss a suitably strong damping mechanism.

Here, we have explored an alternative idea for the origin of these satellites. Our conjecture was the following. When Pluto was still embedded in a massive planetesimal disk, several planetesimals got temporarily captured in the Pluto-Charon system. Some of these planetesimals were subsequently disrupted by collisions with other planetesimals on heliocentric orbits. The debris generated by these disruptions formed a collisionally dissipative disk, whose eccentricities and inclinations eventually damped to zero. Thus the disk turned into an accretional particle disk and the small satellites could be formed.

We have explored quantitatively this idea. We found that temporary capture of planetesimals in the Pluto-Charon system occurs with non-negligible probability only if the planetesimal disk has a quite low dynamical excitation (i.e. eccentricities only up to ~ 0.03 and inclinations up to half this value). However, the typical capture time is only about 100y, much shorter than the collisional lifetime of objects large enough to carry a sufficient amount of mass to form the small Pluto satellites. Thus, the captured objects should have survived intact and should have not generated a disk of debris around Pluto. Therefore, we conclude that the scenario that we envisioned is not viable.

Youdin et al (2012) have recently proposed an alternative idea linked to the possible formation of Pluto-Charon binary in a gravitational collapse scenario (Nesvorný et al, 2010). In this framework, Pluto's outer moons would have formed from a plutocentric disk composed of material leftover in the gravitational collapse process on orbits bound to Pluto. The idea is appealing, but the accretion of massive Kuiper belt binaries by collapsing swarms of solids has yet to be investigated in details.

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