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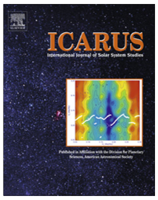

The evolution of a Pluto-like system during the migration of the ice giants

Pryscilla Pires [a,*], Silvia M. Giuliatti Winter [a], Rodney S. Gomes [b]

[a] Univ. Estadual Paulista – UNESP, Grupo de Dinâmica Orbital e Planetologia, Av. Ariberto Pereira da Cunha, 333, Guaratinguetá-SP 12516-410, Brazil
[b] Observatório Nacional, R. Gen. José Cristino, 77, Rio de Janeiro-RJ 20921-400, Brazil

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ABSTRACT

The planetary migration of the Solar System giant planets in the framework of the Nice model (Tsiganis, K., Gomes, R., Morbidelli, A., Levison, H.F. [2005]. Nature 435,459–461; Morbidelli, A., Levison, H.F., Tsiganis, K., Gomes, R. [2005]. Nature 435, 462–465; Gomes, R., Levison, H.F., Tsiganis, K., Morbidelli, A. [2005]. Nature 435, 466–469) creates a dynamical mechanism which can be used to explain the distribution of objects currently observed in the Kuiper belt (e.g., Levison, H.F., Morbidelli, A., Vanlaerhoven, C., Gomes, R., Tsiganis, K. [2008]. Icarus 196, 258–273). Through this mechanism the planetesimals within the disk, heliocentric distance ranging from beyond Neptune's orbit to approximately 34 AU, are delivered to the belt after a temporary eccentric phase of Uranus and Neptune's orbits. We reproduced the mechanism proposed by Levison et al. to implant bodies into the Kuiper belt. The capture of Pluto into the external 3:2 mean motion resonance with Neptune is associated with this gravitational scattering model. We verified the existence of several close encounters between the ice giants and the planetesimals during their outward radial migration, then we believe that the analysis of the dynamical history of the plutonian satellites during this kind of migration is important, and would provide some constrains about their place of formation – within the primordial planetesimal disk or *in situ*. We performed *N*-body simulations and recorded the trajectories of the planetesimals during close approaches with Uranus and Neptune. Close encounters with Neptune are the most common, reaching approximately 1200 in total. A Pluto similarly sized body assumed the hyperbolic trajectories of the former primordial planetesimal with respect to those giant planets. We assumed the current mutual orbital configuration and sizes for Pluto's satellites, then we found that the rate of destruction of systems similar to that of Pluto with closest approaches to Uranus or Neptune <0.10 AU is 40%, i.e. these close approaches can lead to ejections of satellites or to changes in the satellites eccentricities at least 1 order of magnitude larger than the currently observed. However, we also found that the number of closest approaches which the minimum separation to Uranus or Neptune <0.10 AU is negligible, reaching 6%. In the other 60% of close encounter histories with closest approaches >0.10 AU, none of the systems have been destroyed. The latter sample concentrates 94% of closest approaches with the ice giants. Recall that throughout the early history of the Solar System giant impacts were common (McKinnon, W.B. [1989]. Astrophys. J. 344, L41–L44; Stern, A. [1991]. Icarus 90; Canup, R.M. [2005]. Science 307, 546–550). Also, impacts capable of forming a binary like Pluto-Charon can occur possibly prior to 0.5–1 Gyr (Kenyon, S.J., Bromley, B.C. [2014]. Astron. J. 147, 8), and small satellites such as Nix and Hydra can grow in debris from the giant impact (e.g., Canup, R.M. [2011]. Astron. J. 141, 35). Thus, we conclude that if Pluto and its satellites were emplaced into the KB from lower heliocentric orbits, then the Pluto system could survive the encounters that may have happened for emplacement of the Plutinos through the mechanism proposed by Levison et al.

1. Introduction

The dwarf planet Pluto is a member of the trans-Neptunian belt, also known as Edgeworth-Kuiper belt (KB or Kuiper belt, hereafter), a complex structure of numerous bodies orbiting the Sun beyond Neptune's orbit up to about 60 astronomical units (AU). Estimates give that the current mass is within the range 0.01–0.1 Earth masses (Gladman et al., 2001; Bernstein et al., 2004; Chiang et al., 2007), which means that the belt has lost a large fraction of its original mass, about 10–30 Earth masses (Stern, 1996; Stern and Colwell, 1997; Kenyon and Luu, 1998;

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* Corresponding author. Fax: +55 12 3123 2868.
E-mail address: pos09032@feg.unesp.br (P. Pires).

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Kenyon and Luu, 1999; Kenyon and Bromley, 2004), over the years. Numerical simulations such as those in Tsiganis et al. (2005), Morbidelli et al. (2005), and Gomes et al. (2005) – *Nice* model – require the original planetesimal disk mass to be ∼35 Earth masses. The simulations of Gomes et al. (2005) aimed to explain the origin of the *late heavy bombardment* (LHB) of the inner Solar System. The model of Gomes et al. yield the quantity of approximately 0.14 Earth masses for the current trans-Neptunian disk.

Today there are 1260 objects classified as trans-Neptunian objects[1] (TNOs) with absolute visual magnitude up to 12.4. Many TNOs are locked in external $p : q$ mean-motion resonances (MMRs) with Neptune, where p and q are integers. This means that the orbital period of a TNO captured into resonance is a nearly integer multiple with that of Neptune. Some resonances have a large number of bodies, such as 3:2 (whose members are known as Plutinos), 5:3, 7:4, 2:1 and 5:2. The fraction of TNOs locked in MMRs with Neptune ranges from 10% to 20% (Trujillo and Brown, 2001; Kavelaars et al., 2009). Regarding the plutino population, estimates give the existence of approximately 25,000 with diameters larger than 50 km (Kavelaars et al., 2009; Murray-Clay and Schlichting, 2011).

Pluto is the largest body in 3:2 resonance with Neptune and one of the numerous multiple system in the outer Solar System. So far, five satellites were observed around Pluto: Charon (Christy and Harrington, 1978), Nix and Hydra (Weaver et al., 2006), Kerberos and Styx (Showalter et al., 2012; Showalter et al., 2013). Charon is the largest satellite, with a diameter of about 1200 km and an enough mass to be in a nearly round shape. The Charon/Pluto mass ratio is 0.1163 (Tholen et al., 2008), which implies that the Pluto-Charon center of mass is outside Pluto. Each member of the binary rotates every 6.4 days, and the Pluto-Charon system has a 6.4 days orbit. Thus, the pair is in a double synchronous state.

The small satellites are most likely to have irregular shapes; Nix's radius is estimated to be 44 km, while those of Styx, Kerberos and Hydra are ∼5 km, 7 km and 36 km, respectively. To obtain the radii for Nix and Hydra, Tholen et al. (2008) assumed a Charon-like density of 1.63 g/cm^{-3}, while to obtain the sizes of Styx and Kerberos, Showalter et al. (2012, 2013) assumed geometric albedos of 0.35, comparable to that of Charon. All four small moons lie outside Charon's orbit with semimajor axes approximately 42,000–66,000 km from the center of mass of the system (e.g., Buie et al., 2006; Tholen et al., 2008; Showalter et al., 2013), forming a very compact multiple system. The stability of Nix and Hydra were discussed in Nagy et al. (2006) and Pires dos Santos et al. (2011), while Youdin et al. (2012) showed that the stability of Kerberos, over the age of the Solar System, requires lower masses for Nix and Hydra of the order of 10^{16} kg. None of the three cited references has shown that Styx is in a stable orbit. Although, it might be as close as possible to the innermost stable orbit around Pluto-Charon (Pires dos Santos et al., 2011; Kenyon and Bromley, 2014).

Nowadays, it is largely accepted that a giant impact between two similarly sized bodies originated the Pluto-Charon binary (McKinnon, 1989; Canup, 2005). The origin of Charon through a giant impact is favoured due to the high angular momentum of the Pluto system, as well as a giant collision is also favoured to model the formation of the Earth–Moon pair (Canup and Asphaug, 2001; Canup, 2004). Through smooth particle hydrodynamic simulations Canup (2005) showed that the formation of Charon is viable in a large oblique collision. The results show the formation of the binary as a result of such collision, with Charon in a very eccentric orbit relative to Pluto ($e < 0.8$) and very close to it (a approximately 3–15 Pluto's radii, R_p, where 1 R_p corresponds to ∼1150 km). At the time of the satellite's formation, Pluto was spinning fast. Torques due to tides raised by Charon on Pluto transferred angular momentum from the spin of the primary to the orbit of Charon, thus the satellite evolved to its present orbit and had its eccentricity damped, while Pluto's spin period slowed down (e.g.,Fernandez and Ip, 1984). For comparison, the current semimajor axis and eccentricity of Charon are ∼17R_p and 0.0035 (Tholen et al., 2008), respectively.

The model of Canup (2011) suggests that debris from the Charon-forming impact (Canup, 2005) lead to the formation of the small plutonian satellites. However, the main issue with Canup's model is that most of the material from the impact resides in a ring just outside the binary system (a up to 30 R_p), while the current orbital radii of the satellites are larger than that. It remains to be show how these tiny bodies achieved their current distances.

The origin of the smaller satellites is heavily debated (e.g., Lithwick and Wu, 2008a; Cheng, 2011; Peale et al., 2011), and many scenarios have been proposed (Stern et al., 2006; Ward and Canup, 2006; Lithwick and Wu, 2008b; Pires dos Santos et al., 2012). The most promising scenario is that of Kenyon and Bromley (2014), who show that throughout the early history of the Solar System, giant impact that produces the Pluto-Charon binary could happen in a non-negligible rate. After the impact, both Pluto and Charon accrete and eject the debris around the binary to $a \sim 20$ Pluto's radii. The massive circumbinary disk surrounding Pluto-Charon was composed of 0.1–1 km particles, and the binary transferred angular momentum to the disk or ring. As a consequence, the disk has spread close to the current positions of Styx-Hydra. After the collisional damping has overcome the secular perturbations from the binary, small satellites growth began. As the satellites grow, they scatter away smaller objects and migrate through the disk. At the end, Kenyon and Bromley were able to show that the mechanism of collisional evolution within a ring or a disk of debris can yield satellites, especially with radius between 10 and 80 km, at similar positions as Pluto's known small satellites.

At this time, we will briefly present scenarios from the literature that have been proposed to explain the origin of the resonance-locked orbit of Pluto and the Kuiper belt formation. After, we will explain why we choose to use one of them as a framework.

The theory presented by Malhotra (1993, 1995) have been proposed to explain how Pluto ended up occupying the 3:2 MMR with Neptune. This theory is based on the late stages of the planetary formation, when the giant planets were already formed and they were scattering away the remnant planetesimal debris in the interplanetary region. Briefly, as Jupiter effectively ejects those planetesimals scattered inwards by Uranus and Neptune onto hyperbolics orbits, Uranus and Neptune moved considerably outwards due to the angular momentum conservation. This way, the exterior mean motion resonances with Neptune moved outwards as well, capturing not only Pluto in resonance, but also other KBOs – Kuiper belt objects. In these models the test particles were spread to at least ∼50 AU in near-circular and low-inclination orbits, and the high eccentricity of Pluto would be a consequence of the capture into resonance caused by the outward migration of Neptune.

In the light of Pluto's current orbital eccentricity, Malhotra (1993) estimates that an initially circular Pluto migrated at least ∼5 AU after its capture into 3:2 MMR with Neptune. An issue with this model is that the 3:2 population presents a distinct inclination distribution – objects with low and high inclinations. The "resonance capture mechanism" does not explain the different inclination distribution observed in this population (Gomes, 2003). To overcome this problem, the primordial disk should match the current inclination distribution of this population (Hahn and Malhotra, 2005; Levison et al., 2008; Murray-Clay and Schlichting, 2011).

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[1] Minor Planet Public Data Center: http://www.minorplanetcenter.net/iau/lists/t_tnos.html.

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