Plutino (15810) 1994 JR1, an accidental quasi-satellite of Pluto

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ABSTRACT

In the Solar system, quasi-satellites move in a 1:1 mean motion resonance going around their host body like a retrograde satellite but their mutual separation is well beyond the Hill radius and the trajectory is not closed as they orbit the Sun, not the host body. Although they share the semi-major axis and the mean longitude of their host body, their eccentricity and inclination may be very different. So far, minor bodies temporarily trapped in the quasi-satellite dynamical state have been identified around Venus, the Earth, the dwarf planet (1) Ceres, the large asteroid (4) Vesta, Jupiter and Saturn. Using computer simulations, Tiscareno & Malhotra have predicted the existence of a small but significant population of minor bodies moving in a 1:1 mean motion resonance with Pluto. Here we show using N-body calculations that the plutino (15810) 1994 JR1 is currently an accidental quasi-satellite of Pluto and it will remain as such for nearly 350,000 years. By accidental we mean that the quasi-satellite phase is triggered (or terminated) not by a direct gravitational influence in the form of a discrete close encounter, but as a result of a resonance. The relative mean longitude of the plutino (15810) 1994 JR1 circulates with a superimposed libration resulting from the oscillation of the orbital period induced by the 2:3 mean motion resonance with Neptune. These quasi-satellite episodes are recurrent with a periodicity of nearly 2 Myr. This makes the plutino (15810) 1994 JR1, the first minor body moving in a 1:1 mean motion resonance with Pluto and the first quasi-satellite found in the trans-Neptunian region. It also makes Pluto the second dwarf planet, besides Ceres, to host a quasi-satellite. Our finding confirms that the quasi-satellite resonant phase is not restricted to small bodies orbiting major planets but is possible for dwarf planets/asteroids too. Moreover, the plutino (15810) 1994 JR1 could be considered as a possible secondary target for NASA’s Pluto–Kuiper Belt Mission New Horizons after the main Pluto flyby in 2015. This opens the possibility of studying at first hand and for the first time a minor body in the quasi-satellite dynamical state.

Key words: celestial mechanics – kuiper belt: general – minor planets, asteroids: general – minor planets, asteroids: individual: (15810) 1994 JR1 – planets and satellites: individual: Pluto.

1 INTRODUCTION

Quasi-satellites are minor bodies that share the semi-major axis and the mean longitude of their host body but may have different eccentricity and inclination. They move like a retrograde satellite but their separation is well outside the Hill sphere of the host body and the trajectory is not closed; therefore, they are not bound satellites as they orbit the Sun not the host body. The theory behind these remarkable objects was first studied in 1913 (Jackson 1913) but the topic was largely neglected by the scientific community until the end of the twentieth century when the co-orbital motion of planets and asteroids started receiving more attention on theoretical grounds (Mikkola & Innanen 1997; Wiegert, Innanen & Mikkola 2000). So far, such quasi-satellites have been found around Venus (Mikkola et al. 2004), the Earth (Wiegert, Innanen & Mikkola 1997; Connors et al. 2002; Brassier et al. 2004; Connors et al. 2004; Christou & Asher 2011), the dwarf planet (1) Ceres and the large asteroid (4) Vesta (Christou & Wiegert 2012), Jupiter (Kinoshi & Nakai 2007; Wajer & Królickowska 2012) and Saturn (Gallardo 2006). Quasi-satellite orbits around Uranus and Neptune have been predicted to be stable for up to 1 billion years (Wiegert et al. 2000) but no candidate objects have been found there yet.

If quasi-satellites have been discovered orbiting rocky bodies in the inner Solar system and theory predicts long-term stability for quasi-satellite orbits in the outer Solar system, one may wonder whether a quasi-satellite could orbit an object like the dwarf planet Pluto. The existence of a small but significant population of minor bodies experiencing co-orbital resonant behaviour with respect to...
Pluto in the form of libration or slow circulation of the relative mean longitude has been predicted in the context of chaotic diffusion of trans-Neptunian objects (Yu & Tremaine 1999; Tiscareno & Malhotra 2009). Such objects may experience relatively close, low-velocity encounters with Pluto which translate into comparatively large perturbational effects if they occupy the Kozai resonance (Tiscareno & Malhotra 2009). Using data from JPL’s HORIZONS system (http://ssd.jpl.nasa.gov/horizons) we performed a numerical survey looking for minor bodies relatively close to Pluto during the next few years in order to find candidates for possible co-orbital resonant behaviour. Our search resulted in a promising candidate, (15810) 1994 JR1. We identified the plutino (15810) 1994 JR1; as currently located at about 3.1 au from Pluto and slowly approaching its peripluto at 2.7 au within a time frame of 5 years. The object was originally discovered with the 2.5-m Isaac Newton Telescope at La Palma on 1994 May 12 (Irwin et al. 1994; Irwin, Tremaine & Żytkow 1995) and it has a diameter of 251 km (Irwin et al. 1995). Its orbit, which is quite reliable, has been computed using 43 observations with an arc length of 2236 d (http://www.minorplanetcenter.net/db_search/show_object?object_id=1994+JR1), and its UBVRI colours have also been obtained (Barucci et al. 1999).

In this Letter and with the help of N-body calculations, we show that the plutino (15810) 1994 JR1 currently follows a quasi-satellite path around Pluto. This Letter is organized as follows. In Section 2, we briefly outline our numerical model. Section 3 presents and discusses our results. Our conclusions are summarized in Section 4.

2 NUMERICAL MODEL

In order to investigate the orbital evolution of the plutino (15810) 1994 JR1 and its possible co-orbital resonant behaviour with respect to Pluto, we have performed N-body calculations in both directions of time. The numerical integrations of the orbit of the plutino (15810) 1994 JR1, presented here were computed with the Hermite integrator (Makino 1991; Aarseth 2003), in a model Solar System which included the perturbations by the eight major planets (Mercury to Neptune) and treated the Earth and the Moon as a point mass. For the objects in these orbits are called Trojans. Our object, however, does not follow a classical tadpole or horse-shoe behaviour after leaving its quasi-satellite path due to the slow circulation likely induced by the close approaches with Pluto. The actual quasi-satellite phase lasts nearly 350 000 years. Before and after the actual quasi-satellite state, the object does not follow the classical compound orbits resonating between the Trojan and quasi-satellite dynamical states typical of other quasi-satellites (e.g. 2002 V{\text{E}}_5{\text{B}}, Mikkola et al. 2004). These compound orbits have been described on theoretical grounds (Namouni 1999; Namouni, Christou & Murray 1999). The evolution of the semi-major axis over the plotted periods (Figs 2 and 3) remains fairly stable and its average path slowly drifting towards the L5 Lagrangian point. This will happen about 250 000 years from now. The long-term evolution of the orbital elements of the plutino (15810) 1994 JR1, displayed in Fig. 3 shows that the eccentricity exhibits ~0.5 Myr periodic variations, likely the result of an unidentified secular resonance. The

3 ORBITAL EVOLUTION

The heliocentric orbits of both the plutino (15810) 1994 JR1 and the barycentre of the Pluto–Charon system (panels A and B) as well as the quasi-satellite motion features (panels C and D) are shown in Fig. 1. The motion of the plutino (15810) 1994 JR1 from 2012 to 17 012 (the origin of time = JD 245 6200.5, 2012 September 30.0) shows quasi-satellite loops (‘corkscrew’ orbits) as viewed from above Pluto (panel C) and from a point outside Pluto’s orbit looking past Pluto towards the Sun (panel D), in a frame of reference revolving with Pluto. Each loop takes one Plutonian year, 247.7 years. In order to further study the resonant properties of the path shown in Fig. 1 (panels C and D), let us define the relative deviation of the semi-major axis from that of Pluto by \( \alpha = (a - a_P) / a_P \), where \( a \) and \( a_P \) are the semi-major axes of the plutino (15810) 1994 JR1 and Pluto, respectively, and also the relative mean longitude \( \lambda - \lambda_P \), where \( \lambda \) and \( \lambda_P \) are the mean longitudes of the plutino (15810) 1994 JR1 and Pluto, respectively. In Fig. 2 (top panel), the evolution of \( \alpha \) as a function of \( \lambda - \lambda_P \) during the time interval (−25 000, 100 000) years is displayed. The short-period fluctuations are associated with the period of Pluto. In principle, the secular motion is a quasi-harmonic oscillation of the variables \( \lambda - \lambda_P \) and \( \alpha \); this is the main feature of the quasi-satellite motion (Mikkola et al. 2006). In the middle panel, the mean longitude of the plutino (15810) 1994 JR1 relative to Pluto is displayed. The object currently librates asymmetrically around 0° with an amplitude 40°–50° and a period of about 20 000 years that coincides with the libration period of the mean resonant angle of a 2:3 mean motion resonance with Neptune (see below). Here by amplitude we mean the difference between the maximum and the minimum values of the relative mean longitude in a period. The object slowly drifted from the neighbourhood of L4 into the quasi-satellite dynamical state and, in the future, it will move towards L5. L4 is the Lagrange point 60° ahead of Pluto and L5 is the Lagrange point trailing Pluto by 60°; in general, the motion around the Lagrange triangular points follows a tadpole orbit and the objects in these orbits are called Trojans.

Our object, however, does not follow a classical tadpole or horse-shoe behaviour after leaving its quasi-satellite path due to the slow circulation likely induced by the close approaches with Pluto. The actual quasi-satellite phase lasts nearly 350 000 years. Before and after the actual quasi-satellite state, the object does not follow the classical compound orbits resonating between the Trojan and quasi-satellite dynamical states typical of other quasi-satellites (e.g. 2002 V{\text{E}}_5{\text{B}}, Mikkola et al. 2004). These compound orbits have been described on theoretical grounds (Namouni 1999; Namouni, Christou & Murray 1999). The evolution of the semi-major axis over the plotted periods (Figs 2 and 3) remains fairly stable and its average path (proper semi-major axis), 39.4518 au, is very close to that of Pluto, 39.4477 au. All our simulations suggest that the object has remained in the quasi-satellite phase for nearly 100 000 years. In the future, the plutino (15810) 1994 JR1 will leave the quasi-satellite path slowly drifting towards the L4 Lagrangian point. This will happen about 250 000 years from now. The long-term evolution of the orbital elements of the plutino (15810) 1994 JR1, displayed in Fig. 3 shows that the eccentricity exhibits ~0.5 Myr periodic variations, likely the result of an unidentified secular resonance. The
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The object identified in this Letter is not the classical quasi-satellite found around objects moving in not very eccentric orbits like Venus. The high inclination and eccentricity characteristic of the orbit of Pluto add new complexity to an already challenging dynamical situation. In principle, it may be argued that the plutino (15810) 1994 JR$_1$ is not even co-orbital with Pluto, making the analysis carried out here dynamically unjustified. Following Namouni (1999), the co-orbital region in the case of a host object is defined as $|a - a_0| \leq r_{HO}$, where $r_{HO}$ is the radius of the Hill sphere of the host object and $a_0$ its semi-major axis. In the case of the first bona fide quasi-satellite, 2002 VE$_{68}$, and for the JD 245 6200.5 epoch, the semi-major axes of the quasi-satellite and Venus are 0.7237 and 0.7233 au, respectively, and the Hill radius of Venus is 0.0677 au. Therefore, Namouni’s criterion obviously indicates that 2002 VE$_{68}$ is co-orbital with Venus. The same naive application of the criterion to the plutino (15810) 1994 JR$_1$ gives $|39.24–39.36| > 0.0385$ au in violation of the co-orbitality criterion. Therefore, and using this approach, the plutino (15810) 1994 JR$_1$ is not even co-orbital with Pluto and the quasi-satellite motion pointed out above is not more than a happy coincidence. However, if we use the proper...

Figure 1. Orbital evolution of the plutino (15810) 1994 JR$_1$ in the time interval (0, 15 000) years. Panels A and B: the orbits of the plutino (15810) 1994 JR$_1$ (thick line) and Pluto (the barycentre of the Pluto–Charon system) when seen in the heliocentric J2000 ecliptic frame of reference with the $x$-axis aligned towards the vernal equinox. In panel (A) they are seen projected from the direction of the north ecliptic pole (ecliptic plane). In panel (B) the orbits are seen projected from the direction of the vernal equinox. The relatively large difference between the orbital inclination of the plutino (15810) 1994 JR$_1$ ($\sim$0.7237 au) and Pluto ($\sim$0.7233 au) is evident from the figure. Panels C and D: the orbit of the plutino (15810) 1994 JR$_1$, in plutocentric coordinates corotating with Pluto (the barycentre of the Pluto–Charon system). The path oscillates in such a way that when the relative mean longitude librates around 0° (see Fig. 2), Pluto remains inside the path of the plutino (15810) 1994 JR$_1$. The orientation of the asteroid’s orbit allows the path to overlap the position of Pluto without any danger of collision although close approaches are certainly possible (see the text). In all the figures, the origin of time is JD 245 6200.5, 2012 September 30.0.
Figure 2. Resonant evolution of the plutino (15810) 1994 JR1. Top panel: the relative deviation of its semi-major axis from that of Pluto (the barycentre of the Pluto–Charon system), $\alpha$, as a function of the difference between its mean longitude and that of Pluto (the barycentre of the Pluto–Charon system) during the time interval (−25,000, 100,000) years. The relative mean longitude librates around 0$^\circ$ which is the signpost of the quasi-satellite behaviour (Mikkola et al. 2006). Middle panel: mean longitude relative to Pluto, $\lambda - \lambda_P$, over the time interval (−300,000, 300,000) years. The plutino (15810) 1994 JR1 is currently following a quasi-satellite path with the relative mean longitude librating asymmetrically around 0$^\circ$. Bottom panel: semi-major axis evolution. The $\sim$20,000 yr periodic variations induced by the 2:3 mean motion resonance with Neptune are observed in the evolution of the semi-major axis. Initial conditions (nominal orbit) are given in Table 1.

orbital elements instead of osculating Keplerian orbital elements at a particular epoch, the criterion becomes $|39.4518-39.4477| < 0.0401$ au. The proper elements clearly confirm the co-orbital nature (with Pluto) of the plutino (15810) 1994 JR1; it is truly, albeit somewhat accidental, a quasi-satellite of Pluto. By accidental we mean that the quasi-satellite phase is not triggered or terminated by direct gravitational interaction in the form of a discrete close encounter (with a certain planet like the Earth in the case of 2002 VE68) but as a result of a resonance. The relative mean longitude of the plutino circulates with a superimposed libration resulting from the oscillation of the orbital period induced by the 2:3 mean motion resonance with Neptune. These quasi-satellite episodes are recurrent with a periodicity of nearly 2 Myr. The behaviour found in our calculations has been previously described in numerical simulations (Yu & Tremaine 1999; Tiscareno & Malhotra 2009) which predict that only 7 per cent of objects are expected to experience persistent circulation of the relative mean longitude with respect to Pluto; therefore, the identification of one of these unusual objects provides a useful constraint for models studying the dynamics of the outer Solar system as well as giant planet migration. Regarding the origin of the plutino (15810) 1994 JR1, its currently very stable orbit suggests that it is not relatively recent debris originated in collisions within Pluto’s system but perhaps a primordial plutino formed around the same epoch at which Pluto came into existence. The object studied here may be part of an outer Solar system analogue to the population of Main Belt asteroids recently found co-orbiting with the dwarf planet (1) Ceres and the large asteroid (4) Vesta (Christou & Wiegert 2012). Although the figures have been computed using the nominal orbit in Table 1, the other simulations gave very similar results, over the time interval shown.

4 CONCLUSIONS

Pluto’s system continues to be a source of controversy, unanswered questions and surprises more than 80 years after its discovery. Pluto’s planethood demotion in 2006 August still stirs debate and the recent finding of a fifth moon orbiting Pluto by the HST (http://hubblesite.org/newscenter/archive/releases/solar-system/pluto/2012/32/) just confirms the unexpectedly complex nature of the system. In our work, we show that the plutino (15810) 1994 JR1 currently follows a quasi-satellite orbit relative to Pluto; therefore, besides having five regular satellites, Pluto has at least one quasi-satellite. This makes the plutino (15810) 1994 JR1 the first minor body found moving in a 1:1 mean motion resonance with Pluto and the first quasi-satellite found in the trans-Neptunian region of the Solar system. It also makes Pluto the second dwarf planet, besides Ceres, to host a quasi-satellite. Our finding also confirms that the quasi-satellite resonant phase is not restricted to small bodies orbiting major planets, but is possible for dwarf planets/asteroids too. We also provide a new and somewhat unexpected mechanism to land minor bodies into the quasi-satellite dynamical state. On the other hand, the plutino (15810) 1994 JR1 is a natural candidate for a spacecraft rendezvous mission in the framework of NASA’s Pluto–Kuiper Belt Mission.
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New Horizons which is going to complete a flyby with Pluto in 2015 and then continue to explore one or more nearby trans-Neptunian objects in the time frame 2016–2020. It is moving in such an orbit that this object could be a good candidate for a body dynamically related to the Pluto–Charon formation event, and the determination of the physical properties of its surface by spectroscopic observations could be interesting in that respect. If the plutino (15810) 1994 JR$_1$ is selected for the extended mission, it will open the possibility of studying in detail for the first time a minor body in the quasi-satellite dynamical state.

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