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LETTER TO THE EDITOR

(309239) 2007 RW$_{10}$: a large temporary quasi-satellite of Neptune

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ABSTRACT

Context. Upon discovery, asteroid (309239) 2007 RW$_{10}$ was considered a Neptune Trojan candidate. The object is currently listed by the Minor Planet Center as a Centaur but it is classified as a scattered disk or trans-Neptunian object by others. Now that its arc-length is 8154 d and has been observed for more than 20 yr, a more robust classification should be possible.
Aims. Here we explore the orbital behaviour of this object in order to reveal its current dynamical status.
Methods. We perform *N*-body simulations in both directions of time to investigate the evolution of its orbital elements. In particular, we study the librational properties of the mean longitude.
Results. Its mean longitude currently librates around the value of the mean longitude of Neptune with an amplitude of nearly 50° and a period of about 7.5 kyr. Our calculations show that it has been in its present dynamical state for about 12.5 kyr and it will stay there for another 12.5 kyr. Therefore, its current state is relatively short-lived. Due to its chaotic behaviour, the object may have remained in the 1:1 mean motion resonance with Neptune for several 100 kyr at most, undergoing transitions between the various resonant states.
Conclusions. (309239) 2007 RW$_{10}$ is currently a quasi-satellite, the first object of this dynamical class to be discovered around Neptune. With a diameter of about 250 km, it is the largest known co-orbital in the solar system. Although it is not a Centaur now, it may become one in the future as it appears to move in an unstable region. Its significant eccentricity (0.30) and inclination (36°), strongly suggest that it did not form in situ but was captured, likely from beyond Neptune. With an apparent magnitude of 21.1 at opposition (October), it is well suited for spectroscopic observations that may provide information on its composition and hence eventually its origin.

Key words. minor planets, asteroids: general – minor planets, asteroids: individual: (309239) 2007 RW$_{10}$ – celestial mechanics – methods: numerical

1. Introduction

Minor planet (309239) 2007 RW$_{10}$ was discovered by the Palomar Distant Solar System Survey on September 9, 2007 (Schwamb et al. 2007; Schwamb et al. 2010) and reobserved multiple times soon after (Schwamb et al. 2007; Parker et al. 2008). In addition, a number of precovery images of the object were unveiled: it first appears in images obtained as part of the Digitized Sky Survey (DSS) on June 1988 and 1990 from Palomar Mountain and it was pictured again in October 2001 and September 2002 on behalf of the Near-Earth Asteroid Tracking (NEAT) project at Palomar. All this observational material enabled the computation of a very reliable orbit characterized by both significant eccentricity (0.30) and inclination (36°). *Herschel*-PACS observations indicate that the albedo of the object is $8.3^{+6.8}_{-3.9}$% and its absolute magnitude is $H_v = 6.39 \pm 0.61$ which translates into a diameter of 247 ± 30 km (Santos-Sanz et al. 2012). The dynamical status of this object remains controversial. Upon discovery, it was considered a Neptune Trojan candidate[1] but it was reclassified as Centaur shortly afterwards[2]. It is currently listed by the Minor Planet Center (MPC) as a Centaur but it has been classified as a scattered disk object by Santos-Sanz et al. (2012) and the JPL Solar System Dynamics portal includes this asteroid among the trans-Neptunian objects.

Now that its arc-length is 8154 d and the object has been observed for more than 20 yr, a more robust dynamical classification should be possible.

In this Letter, we use *N*-body simulations to study the librational properties of the principal resonant angle of (309239) 2007 RW$_{10}$ with Neptune in order to understand its current dynamical status. The numerical model is described in Sect. 2; the results are presented in Sect. 3 and the long-term orbit behaviour is studied in Sect. 4. Our conclusions are summarized in Sect. 5 after the corresponding discussion.

2. Numerical computations

For accurate initial positions and velocities we used the Heliocentric ecliptic Keplerian elements and their uncertainties provided by the JPL[3] and the AstDyS-2 portal[4] (see Table 1) and initial positions and velocities based on the DE405 planetary orbital ephemerides (Standish 1998)[5] referred to the barycentre of the solar system. The numerical simulations were completed using a Hermite integration scheme (Makino 1991; Aarseth 2003); more details can be found in de la Fuente Marcos & de la Fuente Marcos (2012). Additional calculations were performed using the time-symmetric Hermite method described by Kokubo et al. (1998) but it was found that, for the problem studied here, its

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Table 1. Heliocentric Keplerian orbital elements of (309239) 2007 RW_{10} used in this research.

Semi-major axis, a	=	30.323 ± 0.005 AU
Eccentricity, e	=	0.29957 ± 0.00007
Inclination, i	=	$36.06825 \pm 0.00014°$
Longitude of the ascending node, Ω	=	$187.03214 \pm 0.00007°$
Argument of perihelion, ω	=	$96.734 \pm 0.013°$
Mean anomaly, M	=	$58.95 \pm 0.02°$

Notes. Values include the 1-σ uncertainty. (Epoch = JD 2 456 200.5, 2012-Sep.-30.0; J2000.0 ecliptic and equinox. Source: JPL Small-Body Database and AstDyS-2.)

overall performance was lower and the results almost identical. The standard versions of these direct N-body codes are publicly available from the IoA web site[6]. These versions have been modified in order to study the orbital evolution of (309239) 2007 RW_{10}. Our calculations include the perturbations by eight major planets and treat the Earth and the Moon as two separate objects, they also include the three largest asteroids and the barycentre of the dwarf planet Pluto-Charon system. Orbits are calculated forward and backward in time. In addition to the calculations completed using the nominal orbital elements in Table 1 we have performed 100 control simulations using sets of orbital elements sprinkled from the nominal ones within the accepted uncertainties (3σ) following a Monte Carlo approach.

3. (309239) 2007 RW_{10}: current status

Our main objective is the study of the librational properties of the principal resonant angle of (309239) 2007 RW_{10} in order to reasses its current dynamical class. The principal resonant angle of the object is given by $\lambda_r = \lambda - \lambda_N$, where λ is the mean longitude of the asteroid and λ_N is the mean longitude of Neptune ($\lambda = M + \Omega + \omega$, M is the mean anomaly, Ω is the longitude of the ascending node and ω is the argument of perihelion). If it librates around 0° we have the quasi-satellite state, this is a specific configuration of a 1:1 mean motion resonance, one in which the body librates around the mean longitude of its associated planet; the minor planet orbits the Sun in an approximate ellipse with the same (mean) period as the planet. When viewed in a frame of reference that corotates with the planet, the quasi-satellite follows a retrograde path around the body over the course of an orbital period. Such motion is stabilized by the host planet. The stability of quasi-satellite orbits has been studied by Mikkola et al. (2006). Although brought to the attention of the astronomical community by Mikkola & Innanen (1997), the concept behind the term quasi-satellite was first studied by Jackson (1913) and the associated energetics was first discussed by Hénon (1969). If the principal resonant angle librates around the values +60° or −60° (or 300°), the object is called a Trojan and the associated path, a tadpole orbit. If the libration amplitude is larger than 180°, the path is called a horseshoe orbit. Recurrent transitions between resonant states are possible (quasi-satellite, tadpole, horseshoe) for objects with both large eccentricity and inclination (Namouni et al. 1999). For example, a compound orbit between the Trojan and quasi-satellite states is also called a large-amplitude Trojan when the libration amplitude is less than 180°.

In Fig. 1 we plot λ_r for the nominal orbit in Table 1. The principal resonant angle currently librates around 0°. In celestial mechanics, this is the characteristic property of an object
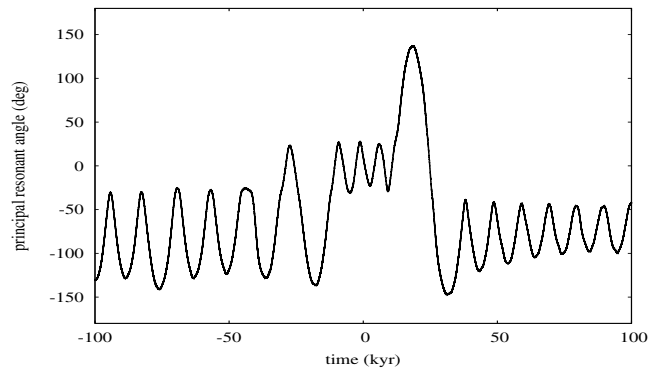
Fig. 1. Evolution of the main resonant angle, $\lambda_r = \lambda - \lambda_N$, of (309239) 2007 RW_{10} over time. It librates around 0° in the time interval ~(–12.5, 12.5) kyr. In all figures, the zero of time is JD 2 456 200.5.
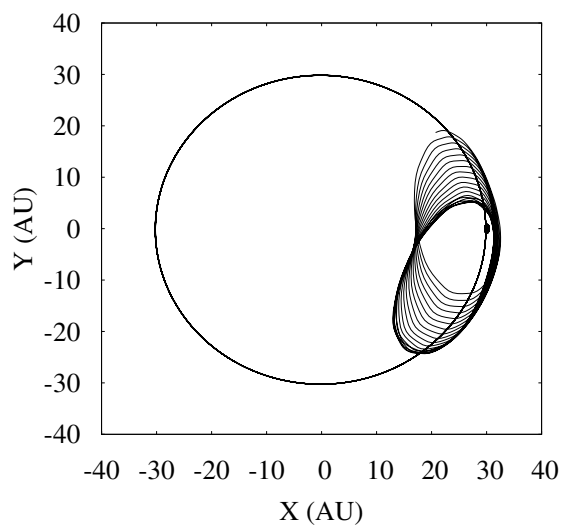

Fig. 2. The motion of (309239) 2007 RW_{10} over the next 3000 yr in a coordinate system rotating with Neptune. The quasi-satellite appears to follow a precessing kidney-shaped path when viewed from Neptune. The orbit and the position of Neptune are also indicated.

in the quasi-satellite dynamical state. In Fig. 2 we plot the motion of the object for the next 3000 yr in a coordinate system that rotates with Neptune. In the rotating coordinate system, the quasi-satellite follows a precessing kidney-shaped retrograde path when viewed from Neptune. Our control calculations produce similar results for the time interval (−13, 24) kyr (see Fig. 3B). Therefore, (309239) 2007 RW_{10} is a quasi-satellite of Neptune; it has remained as such for about 12.5 kyr and it will remain in that state for another 12.5 kyr librating around 0° with amplitude 40°–60° and a period of about 7.5 kyr. Here by amplitude we mean the difference between the maximum and the minimum values of λ_r in a period. These values are similar to those quoted for Neptune Trojans (Zhou et al. 2009, 2011). (309239) 2007 RW_{10} is a temporary quasi-satellite of Neptune which only survives 3 librations of the resonant angle before leaving the state. The current trajectory followed by this object is fairly chaotic, its e-folding time during the quasi-satellite phase is nearly 1 kyr; simulations can only reliably compute the motion of such an object for a time interval not longer than about 50 000 yr. The object is clearly non-primordial. The presence of quasi-satellites around Neptune was predicted by Wiegert et al. (2000); in their paper, it was concluded that the
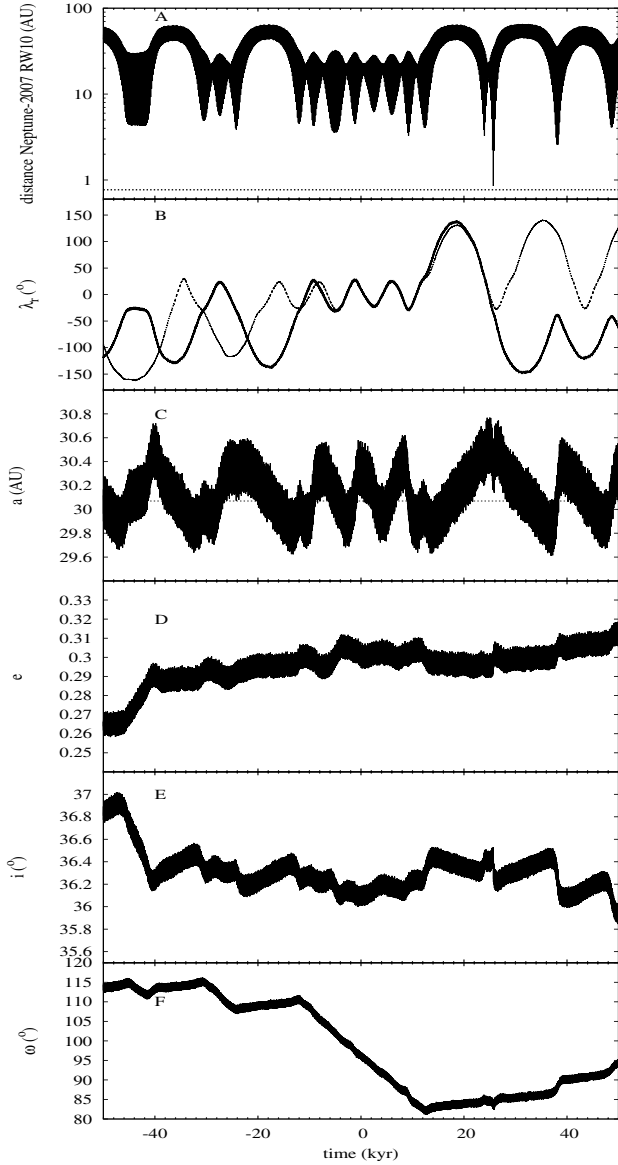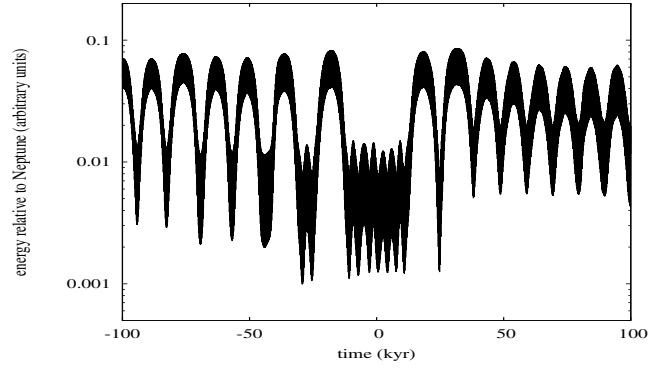
Fig. 4. Total energy (specific orbital energy) of (309239) 2007 RW$_{10}$ relative to Neptune. The quasi-satellite state, even if not bound (energy <0), is clearly less energetic than the other resonant states.

displayed time interval suggesting that encounters with Uranus do not cause the asteroid to depart from the quasi-satellite orbit in either direction of time. However, the distance to the object from Neptune can become as small as 0.86 AU (see Fig. 3A), close to the Hill distance for Neptune that is 0.77 AU. Much closer approaches (even under 0.1 AU) have been observed both in the main simulation and in the control calculations but they fall outside the time range in the figures. Figure 3 (all panels) strongly suggests that the transitional resonant behaviour observed is driven by Neptune as the timings of the various transitions coincide with close encounters between the asteroid and the giant planet. In Figs. 3C−E we illustrate the temporal evolution of the nominal orbit. However, the key parameter here is the argument of perihelion (see Fig. 3F); during the quasi-satellite episodes (even if brief) its value decreases uniformly (in our case, at a rate of $\dot{\omega} = -0.001°$/yr) as predicted by Namouni (1999) but when the object follows a tadpole or horseshoe path, its value increases. In the solar system and for a minor body moving in an inclined orbit, close encounters with major planets are only possible in the vicinity of the nodes. Transfers between quasi-satellite, horseshoe and tadpole orbits are the result of the libration of the nodes (Wiegert et al. 1998). On the other hand, the quasi-satellite dynamical state is characterized by a value of the relative specific orbital energy (see Fig. 4) that is close to the binding border.

5. Discussion and conclusions

From a dynamical standpoint, our calculations indicate that (309239) 2007 RW$_{10}$ is currently a quasi-satellite of Neptune. The object has remained in its current dynamical state for about 12.5 kyr and will continue following that type of orbit for about 12.5 kyr into the future. Although temporary, its present status as quasi-satellite is very robust given the current level of accuracy of the ephemeris and how consistent our results in the time interval (–13, 24) kyr are. On the other hand, the object may have remained in the 1:1 mean motion resonance with Neptune for hundreds of kyr at most, transitioning between the various co-orbital resonant states, as it inhabits a very chaotic region and moves in a dynamically hot orbit. Its significant eccentricity (0.300) is among the largest for any co-orbitals (only Jupiter Trojans like 2010 FH$_{60}$, 0.300, or 2012 BZ$_7$, 0.299, appear to have comparable values) and its high inclination (36°) is the largest among Neptune co-orbitals. These properties and our own results do not favour an scenario in which this object is part of a primordial population of Neptune co-orbitals or the result

Fig. 3. Time evolution of various parameters. The distance of (309239) 2007 RW$_{10}$ from Neptune (panel **A**)); the value of the Hill sphere radius of Neptune, 0.769 AU, is displayed. The resonant angle, λ_r (panel **B**)) for the nominal orbit in Table 1 (thick line) and one of the control orbits (thin line). This particular control orbit has been chosen close to the 3-σ limit so its orbital elements are most different from the nominal ones. The orbital elements a (panel **C**)) with the current value of Neptune's semi-major axis, e (panel **D**)) and i (panel **E**)). The argument of perihelion (panel **F**)) evolves as predicted by Namouni (1999).

outermost planets (Uranus and Neptune) could be the preferred locations to find objects in the quasi-satellite dynamical state.

4. Long-term orbit behaviour: quasi-satellite or Trojan

Our calculations suggest that the present state of the orbit has lasted for about 12.5 kyr but half the control calculations increase that number to 20 kyr (see Fig. 3B). About 12.5 kyr from now, the asteroid will become an L$_4$ large-amplitude Trojan with λ_r librating around +60°. In the past, the object used to be a Trojan around the L$_5$ Lagrangian point. The distance of (309239) 2007 RW$_{10}$ from Uranus remains larger than 4 AU during the

of collisional processes in the vicinity of Neptune. The object is probably an extreme dynamical relative of the L_5 Neptune Trojan 2004 KV_{18}, which is believed to have been originated beyond the orbit of Neptune (Horner & Lykawka 2012). The origin of temporary co-orbitals has recently been discussed by, e.g., Lykawka et al. (2011), Petit et al. (2011) and Gladman et al. (2012) and references inside.

Quasi-satellites have been found around Venus (Mikkola et al. 2004), Earth (Wiegert et al. 1997; Connors et al. 2002; Connors et al. 2004; Brasser et al. 2004; Christou & Asher 2011), the dwarf planet (1) Ceres and the large asteroid (4) Vesta (Christou 2000; Christou & Wiegert 2012), Jupiter (Kinoshita & Nakai 2007; Wajer & Królikowska 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 none have been identified in that region until now. (309239) 2007 RW_{10} is the first bona fide quasi-satellite found around Neptune; as a co-orbital, it adds to the 8 Trojans previously discovered. It is also the largest known object in the 1:1 mean motion resonance with any major planet. The previous record holder was the largest of Jupiter's Trojans, 624 Hektor with a diameter of 203.0 ± 3.6 km (Fernández et al. 2003). With an apparent visual magnitude of 21.1 when at opposition in October and in contrast with known Neptune Trojans, this quasi-satellite is bright enough to be studied spectroscopically to investigate its surface composition. This will provide definite clues on its origin and past evolution.

References

Aarseth, S. J. 2003, in Gravitational N-Body Simulations (Cambridge: Cambridge University Press), 27
Brasser, R., Innanen, K. A., Connors, M., et al. 2004, Icarus, 171, 102
Christou, A. A. 2000, A&A, 356, L71
Christou, A. A., & Asher, D. J. 2011, MNRAS, 414, 2965
Christou, A. A., & Wiegert, P. 2012, Icarus, 217, 27
Connors, M., Chodas, P., Mikkola, S., et al. 2002, Meteor. Planet. Sci., 37, 1435
Connors, M., Veillet, C., Brasser, R., et al. 2004, Meteor. Planet. Sci., 39, 1251
Fernández, Y. R., Sheppard, S. S., & Jewitt, D. C. 2003, AJ, 126, 1563
de la Fuente Marcos, C., & de la Fuente Marcos, R. 2012, MNRAS, in press [arXiv:1208.4444]
Gallardo, T. 2006, Icarus, 184, 29
Gladman, B., Lawler, S. M., Petit, J.-M., et al. 2012, AJ, 144, 23
Hénon, M. 1969, A&A, 1, 223
Horner, J., & Lykawka, P. S. 2012, MNRAS, in press [arXiv:1207.2925]
Jackson, J. 1913, MNRAS, 74, 62
Kinoshita, H., & Nakai, H. 2007, Celest. Mech. Dyn. Astron., 98, 181
Kokubo, E., Yoshinaga, K., & Makino, J. 1998, MNRAS, 297, 1067
Lykawka, P. S., Horner, J., Jones B. W., & Mukai, T. 2011, MNRAS, 412, 537
Makino, J. 1991, ApJ, 369, 200
Mikkola, S., & Innanen, K. 1997, in The Dynamical Behaviour of our Planetary System, eds. R. Dvorak, & J. Henrard (Dordrecht: Kluwer), 345
Mikkola, S., Brasser, R., Wiegert, P., & Innanen, K. 2004, MNRAS, 351, L63
Mikkola, S., Innanen, K., Wiegert, P., Connors, M., & Brasser, R. 2006, MNRAS, 369, 15
Namouni, F. 1999, Icarus, 137, 293
Namouni, F., Christou, A. A., & Murray, C. D. 1999, Phys. Rev. Lett., 83, 2506
Parker, J. E., Kavelaars, J., & Parker, A. 2008, MPEC 2008-X68
Petit, J.-M., Kavelaars, J. J., Gladman, B. J., et al. 2011, AJ, 142, 131
Santos-Sanz, P., Lellouch, E., Fornasier, S., et al. 2012, A&A, 541, A92
Schwamb, M. E., Brown, M. E., Rabinowitz, D., Roe, H. G., & Marsden, B. G. 2007, MPEC 2007-X06
Schwamb, M. E., Brown, M. E., Rabinowitz, D. L., & Ragozzine, D. 2010, ApJ, 720, 1691
Standish, E. M. 1998, JPL Planetary and Lunar Ephemerides, DE405/LE405, Interoffice Memo. 312.F-98-048 (Pasadena, California: Jet Propulsion Laboratory)
Wajer, P., & Królikowska, M. 2012, Acta Astron., 62, 113
Wiegert, P., Innanen, K. A., & Mikkola, S. 1997, Nature, 387, 685
Wiegert, P. A., Innanen, K. A., & Mikkola, S. 1998, AJ, 115, 2604
Wiegert, P., Innanen, K., & Mikkola, S. 2000, AJ, 119, 1978
Zhou, L.-Y., Dvorak, R., & Sun, Y.-S. 2009, MNRAS, 398, 1217
Zhou, L.-Y., Dvorak, R., & Sun, Y.-S. 2011, MNRAS, 410, 1849