A&A 547, L2 (2012)
DOI: 10.1051/0004-6361/201220377

Astronomy & Astrophysics

Letter to the Editor

Four temporary Neptune co-orbitals: (148975) 2001 XA_{255}, (310071) 2010 KR_{59}, (316179) 2010 EN_{65}, and 2012 GX_{17} ⋆

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Received 12 September 2012 / Accepted 10 October 2012

ABSTRACT

Context. Numerical simulations suggest that Neptune primordial co-orbitals may significantly outnumber the equivalent population hosted by Jupiter, yet the objects remain elusive. Since the first discovery in 2001 just ten minor planets, including nine Trojans and one quasi-satellite, have been positively identified as Neptune co-orbitals. In contrast, Minor Planet Center (MPC) data indicate that more than 5000 objects are confirmed Jupiter co-orbitals. On the other hand, some simulations predict that a negligible fraction of passing bodies are captured into the 1:1 commensurability with Neptune today.

Aims. Hundreds of objects have been discovered in the outer solar system during the various wide-field surveys carried out during the past decade, and many of them have been classified using cuts in the pericentre and other orbital elements. This leads to possible misclassifications of resonant objects. Here, we explore this possibility to uncover neglected Neptune co-orbitals.

Methods. Using numerical analysis techniques, we singled out eleven candidates and used N-body calculations to either confirm or reject their co-orbital nature.

Results. We confirm that four objects previously classified as Centaurs by the MPC currently are temporary Neptune co-orbitals. (148975) 2001 XA_{255} is the most dynamically unstable of the four. It appears to be a relatively recent (50 kyr) visitor from the scattered disk on its way to the inner solar system. (310071) 2010 KR_{59} is following a complex horseshoe orbit, (316179) 2010 EN_{65} is in the process of switching from L_4 to L_5 Trojan, and 2012 GX_{17} is a promising L_5 Trojan candidate in urgent need of follow-up. The four objects move in highly inclined orbits and have high eccentricities. These dynamically hot objects are not primordial 1:1 librators, but are captured and likely originated from beyond Neptune, having entered the region of the giant planets relatively recently.

Conclusions. Casting doubt over claims by other authors, our results show that Neptune can still efficiently capture co-orbitals for short periods of time and that the cuts in the orbital elements are unreliable criteria to classify objects orbiting in the outer solar system. As in the case of Jupiter Trojans, our results suggests that Neptune's L_5 point is less stable than L_4, in this case perhaps due to the influence of Pluto.

Key words. methods: numerical – celestial mechanics – minor planets, asteroids: general – Kuiper belt: general

1. Introduction

Numerical simulations predict that Neptune may have retained a significant amount of its primordial co-orbital minor planet population, including Trojans and quasi-satellites (Holman & Wisdom 1993; Wiegert et al. 2000; Nesvorný & Dones 2002; Marzari et al. 2003; Kortenkamp et al. 2004; Dvorak et al. 2007; Nesvorný & Vokrouhlický 2009; Zhou et al. 2009, 2011; Lykawka et al. 2009, 2010, 2011). The first Neptune Trojan, 2001 QR_{322}, was serendipitously discovered by Chiang et al. (2003). 2004 UP_{10}, 2005 TN_{53} and 2005 TO_{74} followed (Sheppard & Trujillo 2006). Then 2006 RJ_{103} and 2007 VL_{305}, all of them leading 60° ahead of Neptune (i.e. they are L_4 Trojans). Shortly after, the first L_5 Trojan, 2008 LC_{18}, was found (Sheppard & Trujillo 2010), followed by the second one, 2004 KV_{18}. These eight Trojans have recently been joined by one short-term quasi-satellite, (309239) 2007 RW_{10} (de la Fuente Marcos & de la Fuente Marcos 2012a) and yet another L_5 Trojan, 2011 HM_{102}, (Tholen et al. 2012; Parker et al. 2012). Confirmed Jupiter co-orbitals currently amount to more than 5000 objects[1]; theoretical and numerical expectations predict even larger numbers for Neptune, although they are harder to detect because they are farther away. On the other hand, it is commonly thought that Neptune cannot efficiently capture objects into the 1:1 commensurability even for short periods of time (Horner & Evans 2006).

During the past decade, wide-field surveys of the outer solar system have found hundreds of objects passing in the neighbourhood of Neptune, many of which were classified using cuts in the pericentre, q, and other orbital elements (for example, the MPC defines that Centaurs must have a perihelion larger than Jupiter's orbit and a semi-major axis shorter than Neptune's). This leads to misclassifications of resonant objects (Shankman 2012). It is possible that some of these objects may have not been properly identified and that they are, in fact, trapped (even if temporarily) in a 1:1 commensurability with Neptune. Here, we explore this possibility and try to uncover misidentified Neptune co-orbitals. In this letter, we use N-body simulations to confirm the possible co-orbital nature with Neptune of a number of objects currently classified as Centaurs by the Minor Planet Center (MPC). The

⋆ Tables 2–4 and Figs. 4–6 are available in electronic form at http://www.aanda.org

[1] http://www.minorplanetcenter.net/iau/lists/JupiterTrojans.html

numerical model is described in the next section and the results are presented in Sects. 3 to 6. The results are discussed and our conclusions summarized in Sect. 7.

2. Candidates and numerical experiments

Following Mikkola et al. (2006) and to study the librational properties of any possible candidates, we define the relative deviation of the semi-major axis from that of Neptune by $\alpha = (a-a_{\rm N})/a_{\rm N}$, where a and $a_{\rm N}$ are the semi-major axes of the object and Neptune, respectively, and also the relative mean longitude $\lambda_{\rm r} = \lambda - \lambda_{\rm N}$, where λ and $\lambda_{\rm N}$ are the mean longitudes of the object and Neptune, respectively. If $\lambda_{\rm r}$ oscillates around 0°, we call the object a quasi-satellite; a Trojan is characterized by $\lambda_{\rm r}$ oscillating around +60° (L_4 Trojan) or –60° (or 300°, L_5 Trojan); finally, an object oscillating with amplitude >180° follows a horseshoe orbit in a frame of reference rotating with Neptune (see, e.g., Murray & Dermott 1999). Objects that switch libration from the Lagrangian point L_4 to L_5 (or vice versa) are called jumping Trojans (Tsiganis et al. 2000). Searching for Neptune co-orbital candidates among known minor bodies with relative semi-major axis $|a - a_{\rm N}| < 2$ AU, we found 21 objects, 10 of which were already documented as co-orbitals. We regarded the remaining 11 as candidates and then used N-body calculations to either confirm or reject their putative co-orbital nature. The orbit computations were completed using a Hermite integration scheme (Makino 1991; Aarseth 2003). The N-body code is publicly available from the IoA web site[2]. Our calculations include the perturbations by the eight major planets, treating the Earth and the Moon as two separate point masses, the barycentre of the Pluto-Charon system, and the three largest asteroids. For accurate initial positions and velocities we used the heliocentric ecliptic Keplerian elements provided by the JPL online solar system data service[3] (Giorgini et al. 1996) and initial positions and velocities based on the DE405 planetary orbital ephemerides (Standish 1998) referred to the barycentre of the solar system. In addition to the orbital calculations completed using the nominal elements in Table 1, we have performed 50 control simulations (for each object) with sets of orbital elements obtained from the nominal ones and the quoted uncertainties (3σ) when available. Additional details can be found in de la Fuente Marcos & de la Fuente Marcos (2012b). We have also validated our simulations against previous work by integrating the orbits of the known nine Neptune Trojans (orbital elements in Tables 2–4), see Figs. 4–6; results are consistent with those from other authors.

3. (148975) 2001 XA_{255}: very dynamically unstable

(148975) 2001 XA_{255} was discovered on December 9, 2001 at Mauna Kea Observatory by Jewitt et al. (2002). It moves in a very eccentric orbit (0.68) with perihelion just inside the orbit of Saturn and significant inclination (12.6°). Its aphelion is in the trans-Neptunian belt. It is classified as an inactive Centaur (Jewitt 2009). Its colours are neutral (Fraser & Brown 2012). (148975) 2001 XA_{255} is the most dynamically unstable of the four objects studied here with an e-folding time (or characteristic timescale on which two arbitrarily close orbits diverge exponentially) of about 300 yr. It is perturbed by Saturn, Uranus, and Neptune. It appears to be a relatively recent (50 kyr) visitor from the scattered disk on its way to the inner solar system.

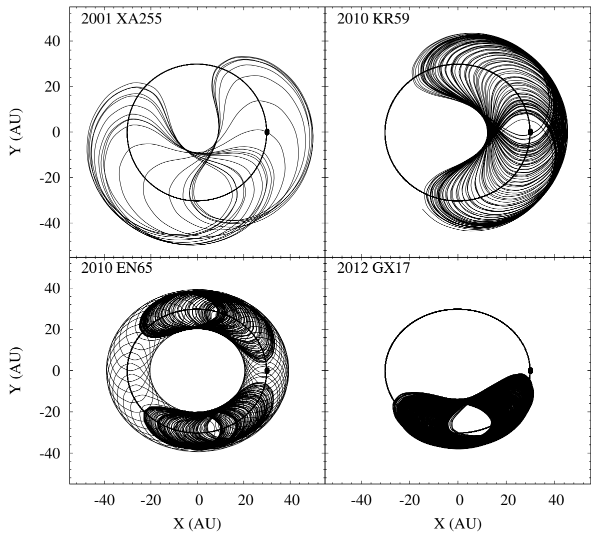

Fig. 1. Motion of the objects in a coordinate system rotating with Neptune. The orbit and position of Neptune are also plotted. The time intervals displayed are 2001 XA_{255} (–1.5, 1.5) kyr, 2010 KR_{59} (5, 20) kyr, 2010 EN_{65} (–20, 20) kyr, and 2012 GX_{17} (–50, 50) kyr.

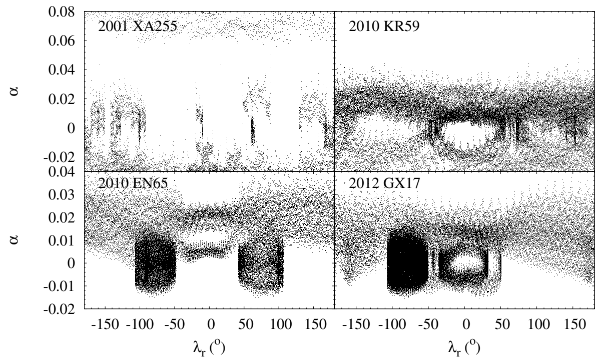

Fig. 2. Resonant evolution. The α parameter (see text for details) as a function of the relative mean longitude during the time interval (–50, 50) kyr, except for 2012 GX_{17}, (–100, 100) kyr.

Calculations suggest that it came from beyond 100–200 AU and it is currently a very short-lived horseshoe librator (see Figs. 1 and 2). It entered the horseshoe orbital path about 10 kyr ago and will leave its present dynamical state 2 kyr from now (see Fig. 3); very close encounters with Neptune are possible. It has previously been identified by Gallardo (2006) as a transition object affected by a 1:1 mean motion resonance with Neptune and 1:2 with Uranus and was classified by Bailey & Malhotra (2009) as a difussing Centaur.

4. (310071) 2010 KR_{59}: a transient horseshoe

Discovered on May 18, 2010 by NASA's Wide-field Infrared Survey Explorer (WISE; Scotti et al. 2010). The WISE telescope scanned the entire sky in infrared light from January 2010 to February 2011 (Wright et al. 2010). (310071) 2010 KR_{59} moves in a very eccentric orbit (0.57) with perihelion outside Saturn's orbit and significant inclination (19.67°). Little is known about this object with the exception of its absolute magnitude of 7.7 (~22 apparent). This suggests a relatively large object with an estimated diameter of about 100 km. Its e-folding time is close to 10 kyr, and it is now pursuing a complicated horseshoe orbit (Fig. 2) in its way to become a short-term quasi-satellite as

[2] http://www.ast.cam.ac.uk/~sverre/web/pages/nbody.htm
[3] http://ssd.jpl.nasa.gov/?planet_pos

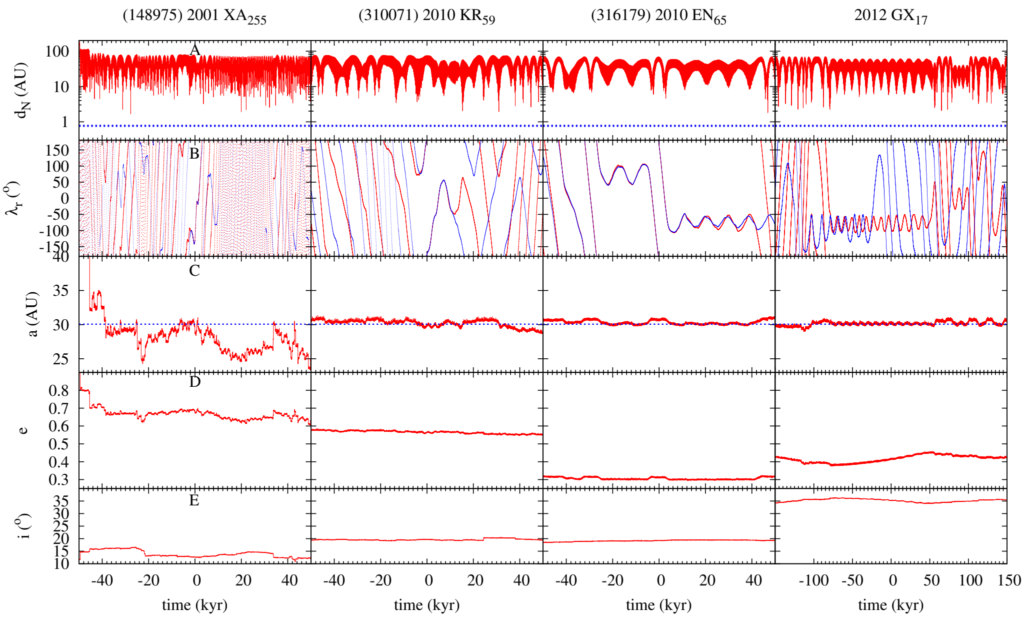

Fig. 3. Time evolution of various parameters for 2001 XA_{255}, 2010 KR_{59}, 2010 EN_{65}, and 2012 GX_{17}. The distance to the object from Neptune, d_N, is shown in panel **A)** and the value of the Hill sphere radius of Neptune, 0.769 AU, is displayed. The resonant angle, λ_r, is shown in panel **B)** for the nominal orbit in Table 1 (thick red line) along with one of the control orbits (thin blue line). This particular control orbit was chosen to lie close to the 3-σ limit so that its orbital elements are distinct from the nominal ones with the exception of 2012 GX_{17}. For that object the control orbit elements deviate by 1% from the nominal values in Table 1, which is at least 25 times higher than those of the other objects. The orbital elements are shown in panel **C)**, a, with the current value of Neptune's semi-major axis, panel **D)**, e, and panel **E)**, i.

depicted in Fig. 1. It will leave the 1:1 resonance with Neptune in a few 100 kyr. Its current horseshoe state started about 100 kyr ago. Dangerously close encounters with Neptune are possible.

5. (316179) 2010 EN_{65}: a jumping Trojan

(316179) 2010 EN_{65} was discovered on March 7, 2010 by Rabinowitz and Tourtellotte using the 1.3-m reflector from Cerro Tololo (Lowe et al. 2010). Upon discovery, the orbit of the object was described as Neptune-like, but its relative mean longitude with respect to Neptune was almost 180°. Up to 19 precovery images were found shortly after, the first one acquired on November 4, 1989 by the Digitized Sky Survey (DSS) from Palomar Mountain. It is the largest of the four objects studied here, perhaps with a diameter of nearly 200 km. It moves in an eccentric orbit (0.31) with perihelion just outside Uranus's orbit and significant inclination (19°). It was classified by Rabinowitz et al. (2012) as a scattered-disk object. Our calculations show that its e-folding time is close to 3 kyr and it is currently moving from the Lagrangian point L_4 to L_5 (see Figs. 1–3). This result is very robust as all the control orbits follow the same orbital behaviour within 40 kyr of the current epoch. We classify this object as a jumping Trojan.

6. 2012 GX_{17}: a promising L_5 Trojan candidate

The minor planet 2012 GX_{17} was discovered by Pan-STARRS 1, Haleakala, Hawaii on March 14, 2012 and was reobserved from Magdalena Ridge Observatory, Socorro, New Mexico on March 18. As a recently discovered object and in sharp contrast with the previous three, its orbit is poorly known and it is mainly included here to encourage follow-up observations: its orbital solution is based on ten observations with an arc length of just four days. The physical properties of this object are unknown with the exception of its absolute magnitude of 7.8 (~22 apparent). This suggests a relatively large object with an estimated diameter in the range 55–180 km (for an albedo range of 0.5–0.05 and an assumed density of 2000 kg m^{-3}). Its period, 165 yr, matches that of Neptune, 164.79 yr, therefore, it appears to follow a 1:1 resonant orbit with Neptune (a = 30.13 AU), yet it has been classified as a Centaur by the MPC. Our calculations for the nominal orbit in Table 1 indicate that the value of the relative mean longitude of 2012 GX_{17} librates around –60° with an amplitude of 40–55° and a period of about 10 kyr; therefore, it appears to be a trailing Trojan (see Figs. 1–3). Although its e-folding time is nearly 10 kyr, it has been an L_5 Trojan for tens of kyr and simulations suggest that it will be leaving its current dynamical state to become a horseshoe librator in about 50 kyr. 2011 HM_{102} was the highest inclination Neptune Trojan known but this candidate has even higher orbital inclination (i = 35°). Due to its poorly known orbit, we must insist that the object is a mere Trojan candidate (and in dire need of follow-up observations) although all studied control orbits (with errors below 1%) give consistent results. Our calculations show that 2012 GX_{17} may have been a passing minor body (perhaps from the scattered-disk) that eventually evolved dynamically into a trailing Neptune Trojan. We also find that compared to Neptune's other Trojans, 2012 GX_{17} is significantly more perturbed by Uranus.

7. Discussion and conclusions

Compared to the eight "classical" Neptune Trojans (2001 QR_{322}, 2004 UP_{10}, 2005 TN_{53}, 2005 TO_{74}, 2006 RJ_{103}, 2007 VL_{305}, 2008 LC_{18}, and 2004 KV_{18}) and the new one (2011 HM_{102}), the objects described here (even if they are currently co-orbitals of Neptune) are much more dynamically hot and their characteristic lifetime as co-orbitals is relatively short, but comparable to that of the most unstable of the other nine objects (2004 KV_{18}, see Figs. 4–6). Dynamically speaking, they are similar to the recently identified temporary Neptunian quasi-satellite (309239)

Table 1. Heliocentric Keplerian orbital elements of the objects studied in this research.

		(148975) 2001 XA_{255}	(310071) 2010 KR_{59}	(316179) 2010 EN_{65}	2012 GX_{17}
Semi-major axis, a (AU)	=	28.8587 ± 0.0010	29.970 ± 0.004	30.719 ± 0.002	30.1330172
Eccentricity, e	=	0.676579 ± 0.000010	0.56676 ± 0.00006	0.31492 ± 0.00004	0.4149134
Inclination, i (°)	=	12.62072 ± 0.00002	19.67387 ± 0.00005	19.24716 ± 0.00003	35.29849
Longitude of the ascending node, Ω (°)	=	105.92560 ± 0.00014	46.7483 ± 0.0003	234.2657 ± 0.0003	207.75190
Argument of perihelion, ω (°)	=	90.3433 ± 0.0004	108.2697 ± 0.0010	225.236 ± 0.003	94.00361
Mean anomaly, M (°)	=	5.3117 ± 0.0002	5.6713 ± 0.0014	36.831 ± 0.005	298.44011
Perihelion distance, q (AU)	=	9.33350 ± 0.00010	12.9842 ± 0.0008	21.0450 ± 0.0009	17.6304246
Absolute magnitude, H (mag)	=	11.2	7.7	6.9	7.8

Notes. Values include the 1-σ uncertainty when available. (Epoch = JD 2456 200.5, 2012-Sep-30.0 except for 2012 GX_{17} that is JD 2 456 020.5, 2012-Apr-3.0; J2000.0 ecliptic and equinox. Sources: JPL Small-Body Database and AstDyS-2.)

2007 RW_{10} (de la Fuente Marcos & de la Fuente Marcos 2012a). The clue to the true origin of all these five objects (and, perhaps, 2004 KV_{18}) could be (148975) 2001 XA_{255}, which clearly came from beyond 100–200 AU. This conclusion is similar to that in Horner & Lykawka (2012) for the case of the Neptune L_5 Trojan 2004 KV_{18}. On the other hand, (316179) 2010 EN_{65} could be the brightest and 2012 GX_{17} the highest inclination Neptune Trojan.

Out of more than 5000 confirmed Jupiter Trojans there is a well-documented asymmetry between the number of bodies in the leading and trailing populations: the Sloan Digital Sky Survey (SDSS) puts the L_4:L_5 Trojan ratio at 1.6 ± 0.1 (Szabó et al. 2007), the *Subaru* telescope survey gives nearly 1.8 (Nakamura & Yoshida 2008; Yoshida & Nakamura 2008) and the latest results from the WISE/NEOWISE mission give 1.4 ± 0.2 (Grav et al. 2011). Prior to this research the L_4:L_5 ratio for Neptune was $6/3 = 2$. Our calculations suggest that Neptune's L_5 point is less stable than L_4, apparently due to the influence of Pluto. All trailing Trojans undergo close approaches within 0.3 AU of Pluto. Close encounters with the dwarf planet can send trailing Trojans into complex paths away from the usual tadpole orbit, inducing jumping Trojan events, temporary quasi-satellite episodes, or throwing the object on a horseshoe orbit. An asymmetry between the Neptunian L_4 and the L_5 swarms was found in numerical integrations by Holman & Wisdom (1993) but, at that time, it was not understood why that asymmetry existed.

It is sometimes claimed that Neptune cannot currently efficiently trap objects in the 1:1 commensurability even for short periods of time. Our results argue that, contrary to this view, Neptune is still actively capturing temporary co-orbitals. This is consistent with recent findings by Kortenkamp & Joseph (2011). These authors conclude that the nearly 2:1 mean motion resonance between Uranus and Neptune facilitates capture of new Neptune co-orbitals. Most of the objects described here are relatively large and a much more numerous population of smaller objects similar to them may exist. We also confirm that dynamical classifications based on cuts in the pericentre and other elements are not very reliable in the case of resonant objects.

Acknowledgements. The authors would like to thank S. Aarseth for providing the code used in this research and the referee, S. Kortenkamp, for his constructive and quick report. This work was partially supported by the Spanish "Comunidad de Madrid" under grant CAM S2009/ESP-1496 (Dinámica Estelar y Sistemas Planetarios). We thank M. J. Fernández-Figueroa, M. Rego Fernández and the Department of Astrophysics of Universidad Complutense de Madrid (UCM) for providing excellent computing facilities. Most of the calculations and part of the data analysis were completed on the "Servidor Central de Cálculo" of the UCM and we thank S. Cano Alsúa for his help during that stage.

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Table 2. Heliocentric Keplerian orbital elements of Neptune's L_4 Trojans (I): 2001 QR_{322}, 2004 UP_{10}, and 2005 TN_{53}.

		2001 QR_{322}	2004 UP_{10}	2005 TN_{53}
semi-major axis, a (AU)	=	30.356 ± 0.007	30.28 ± 0.02	30.262 ± 0.012
eccentricity, e	=	0.02891 ± 0.00010	0.03140 ± 0.00010	0.069 ± 0.002
inclination, i (°)	=	1.3210 ± 0.0006	1.43107 ± 0.00005	24.978 ± 0.003
longitude of the ascending node, Ω (°)	=	151.548 ± 0.015	34.798 ± 0.003	9.2809 ± 0.0002
argument of perihelion, ω (°)	=	167.0 ± 0.4	4 ± 3	84.7 ± 0.4
mean anomaly, M (°)	=	60.3 ± 0.4	345 ± 2	296.7 ± 0.2
perihelion distance, q (AU)	=	29.478 ± 0.005	29.329 ± 0.014	28.176 ± 0.010
absolute magnitude, H (mag)	=	7.7	8.8	9.1

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

Table 3. Heliocentric Keplerian orbital elements of Neptune's L_4 Trojans (II): 2005 TO_{74}, 2006 RJ_{103}, and 2007 VL_{305}.

		2005 TO_{74}	2006 RJ_{103}	2007 VL_{305}
a (AU)	=	30.262 ± 0.013	30.181 ± 0.009	30.195 ± 0.014
e	=	0.0536 ± 0.0009	0.0300 ± 0.0010	0.0684 ± 0.0003
i (°)	=	5.248 ± 0.002	8.1615 ± 0.0003	28.1301 ± 0.0010
Ω (°)	=	169.370 ± 0.006	120.912 ± 0.010	188.5826 ± 0.0010
ω (°)	=	300.5 ± 0.4	17 ± 1	217.6 ± 0.3
M (°)	=	278.7 ± 0.4	257 ± 1	359.2 ± 0.2
q (AU)	=	28.639 ± 0.011	29.276 ± 0.008	28.130 ± 0.012
H (mag)	=	8.5	7.5	8.0

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

Table 4. Heliocentric Keplerian orbital elements of Neptune's L_5 Trojans: 2004 KV_{18}, 2008 LC_{18}, and 2011 HM_{102}.

		2004 KV_{18}	2008 LC_{18}	2011 HM_{102}
a (AU)	=	30.108 ± 0.011	29.90 ± 0.03	30.05 ± 0.05
e	=	0.1847 ± 0.0011	0.086 ± 0.003	0.0785 ± 0.0002
i (°)	=	13.6127 ± 0.0015	27.592 ± 0.006	29.4203 ± 0.0004
Ω (°)	=	235.6308 ± 0.0005	88.5219 ± 0.0012	100.98900 ±0.00006
ω (°)	=	294.2 ± 0.3	8 ± 13	152.05 ± 0.03
M (°)	=	61.19 ± 0.13	173 ± 15	22.48 ± 0.03
q (AU)	=	24.548 ± 0.007	27.327 ± 0.007	27.691 ± 0.004
H (mag)	=	8.9	8.4	8.1

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

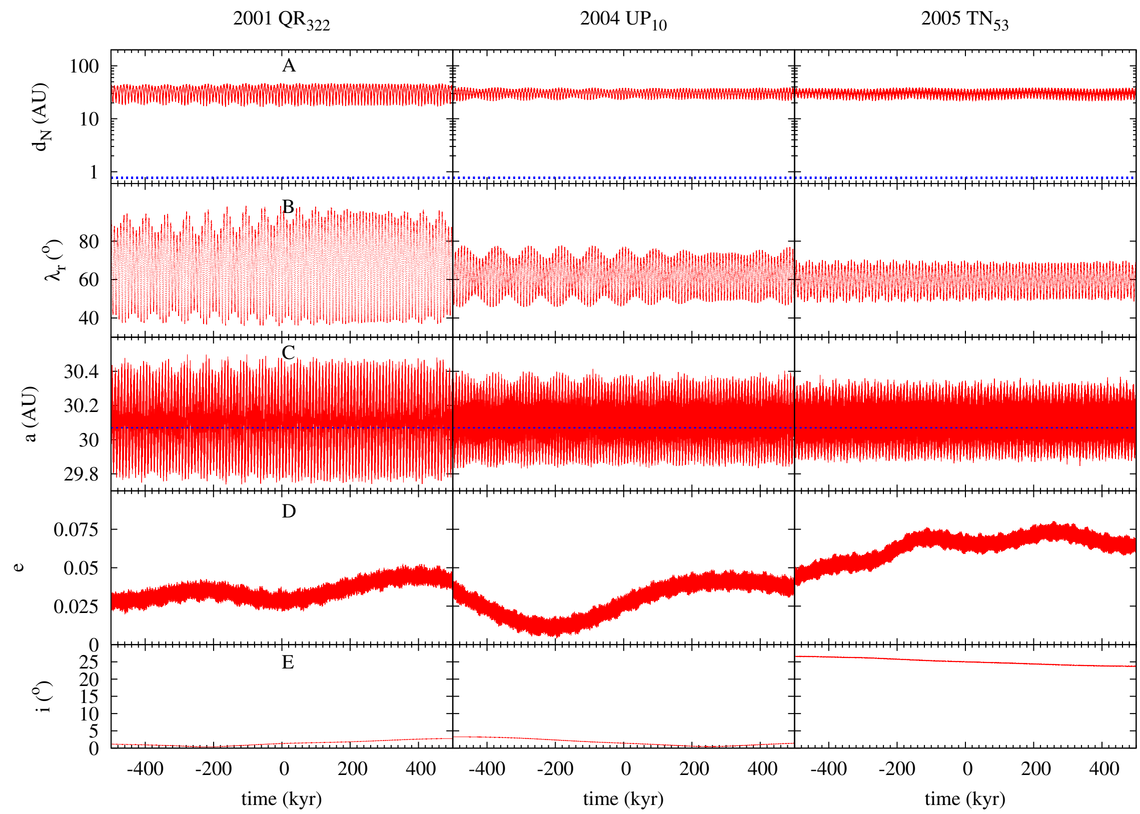

Fig. 4. Evolution of various parameters during the time interval (–500, 500) kyr for three Neptune L_4 Trojans: 2001 QR_{322}, 2004 UP_{10}, and 2005 TN_{53}. The distance to the objects from Neptune is given in panel **A)**; the value of the Hill sphere radius of Neptune, 0.769 AU, is displayed. The resonant angle, λ_r, is displayed in panel **B)** for the nominal orbit (source: JPL Small-Body Database and AstDyS-2). The orbital elements are depicted in panel **C)**, a with the current value of Neptune's semi-major axis, panel **D)**, e, and panel **E)**, i. 2005 TN_{53} appears to be the most stable of Neptune's Trojans and 2001 QR_{322} the one with the largest libration amplitude.

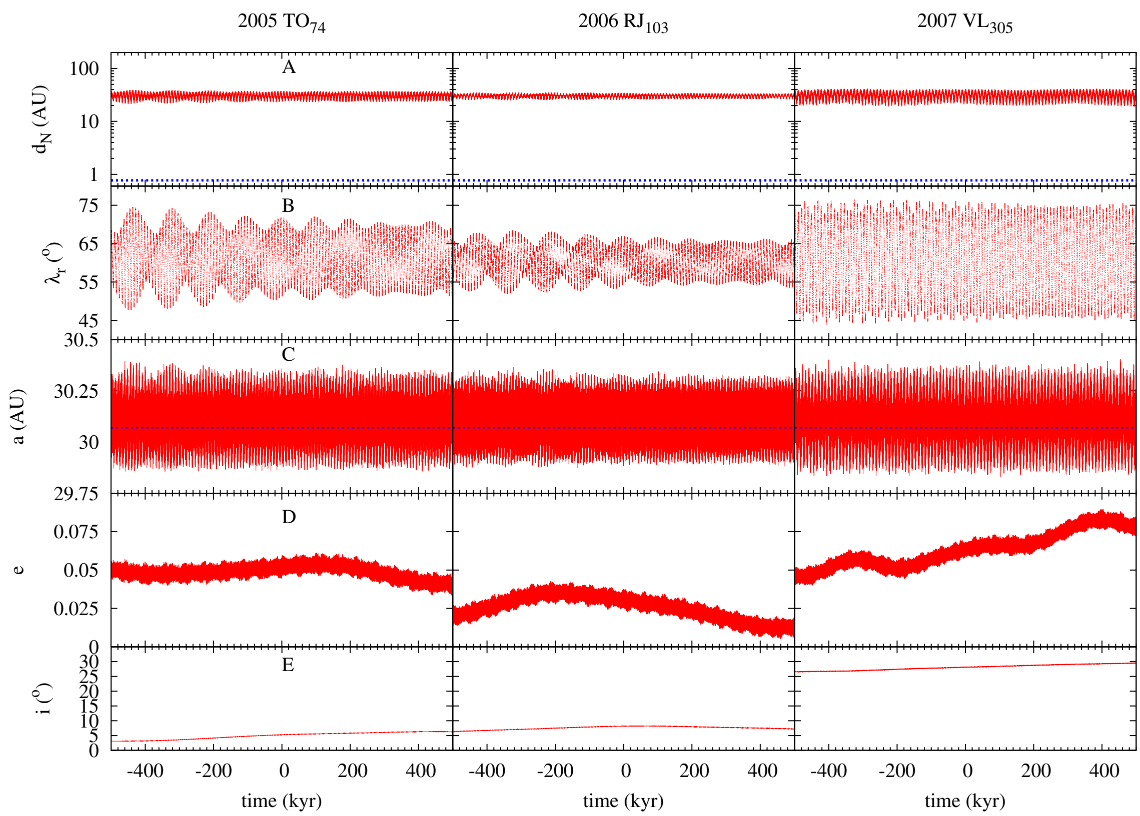

Fig. 5. Same as Fig. 4 but for Neptune L_4 Trojans: 2005 TO_{74}, 2006 RJ_{103}, and 2007 VL_{305}. 2007 VL_{305} exhibits the second largest libration amplitude among L_4 Trojans.

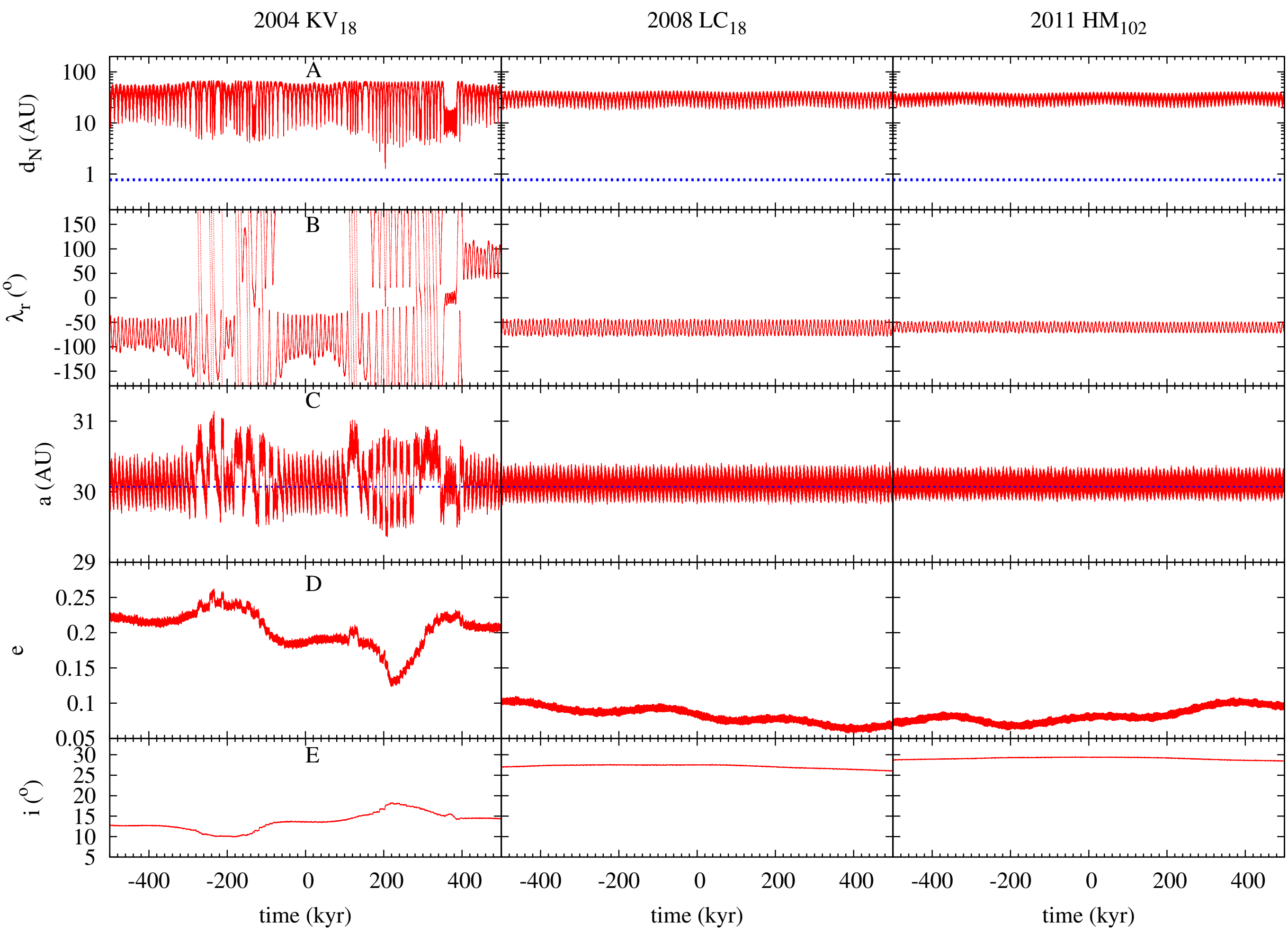

Fig. 6. Same as Figs. 4 and 5 but for Neptune L_5 Trojans: 2004 KV_{18}, 2008 LC_{18}, and 2011 HM_{102}. The dynamical evolution of 2004 KV_{18} is clearly different and it is the most unstable of the "classical" Neptune Trojans. The most recent discovery, 2011 HM_{102}, is the most stable L_5 Trojan and it may be as stable as 2005 TN_{53}, likely the most stable of Neptune's Trojans.