Asteroid 2014 OL$_{339}$: yet another Earth quasi-satellite

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ABSTRACT

Our planet has one permanently bound satellite –the Moon–, a likely large number of mini-moons or transient irregular natural satellites, and three temporary natural retrograde satellites or quasi-satellites. These quasi-moons –(164207) 2004 GU$_9$, (277810) 2006 FV$_{35}$ and 2013 LX$_{28}$– are unbound companions to the Earth. The orbital evolution of quasi-satellites may transform them into temporarily bound satellites of our planet. Here, we study the dynamical evolution of the recently discovered Aten asteroid 2014 OL$_{339}$ to show that it is currently following a quasi-satellite orbit with respect to the Earth. This episode started at least about 775 yr ago and it will end 165 yr from now. The orbit of this object is quite chaotic and together with 164207 are the most unstable of the known Earth quasi-satellites. This group of minor bodies is, dynamically speaking, very heterogeneous but three of them exhibit Kozai-like dynamics: the argument of perihelion of 164207 oscillates around -90°, the one of 277810 librates around 180° and that of 2013 LX$_{28}$ remains around 0°. Asteroid 2014 OL$_{339}$ is not currently engaged in any Kozai-like dynamics.

Key words: celestial mechanics – minor planets, asteroids: individual: 2004 GU$_9$ – minor planets, asteroids: individual: 2006 FV$_{35}$ – minor planets, asteroids: individual: 2013 LX$_{28}$ – minor planets, asteroids: individual: 2014 OL$_{339}$ – planets and satellites: individual: Earth.

1 INTRODUCTION

The term "quasi-satellite" was first used in a scientific publication by Danielsson & Ip (1972) while trying to explain the resonant behaviour of the near-Earth Object (NEO) 1685 Toro (1948 OA). However, this early mention was not directly connected with its current use. It is now generally accepted that the term was first introduced and popularized among the scientific community by Mikkola & Innanen (1997), although the concept behind it was initially studied by Jackson (1913) and the energy balance associated to the resonant state was first explored by Hénon (1969), who coined the term "retrograde" satellites to refer to them. Further analyses were carried out by Szebehely (1967), Broucke (1968), Benest (1976, 1977), Dermott & Murray (1981), Kogan (1989) and Lidov & Vashkov'yak (1993, 1994a,b). Most of this early work was completed within the framework of the restricted elliptic three-body problem. The quasi-satellite dynamical state is a specific configuration of the 1:1 mean motion resonance with a host planet in which the object involved appears to travel around the planet but is not gravitationally bound to it, i.e. the body librates around the longitude of its associated planet but its trajectory is not closed.

The first minor body to be confirmed to pursue a quasi-satellite orbit was 2002 VE$_{68}$ that is companion to Venus (Mikkola et al. 2004). Objects in this dynamical state have been found following Ceres and Vesta (Christou 2000a; Christou & Wiegert 2012), Jupiter (Kinoshita & Nakai 2007; Wajer & Królikowska 2012),

Saturn (Gallardo 2006), Neptune (de la Fuente Marcos & de la Fuente Marcos 2012a) and Pluto (de la Fuente Marcos & de la Fuente Marcos 2012c). So far, Jupiter has the largest number of documented quasi-satellites with at least six, including asteroids and comets (Wajer & Królikowska 2012). Our planet comes in second place with three detected quasi-satellite companions: (164207) 2004 GU$_9$ (Connors et al. 2004; Mikkola et al. 2006; Wajer 2010), (277810) 2006 FV$_{35}$ (Wiegert et al. 2008; Wajer 2010) and 2013 LX$_{28}$ (Connors 2014). As such, these objects are not real, gravitationally bound satellites but, from Earth's point of view, they appear to travel in the retrograde direction around it over the course of a year although they actually orbit (in the prograde direction) the Sun. Large amounts of interplanetary dust particles are also temporarily trapped in Earth's quasi-satellite resonance (Kortenkamp 2013) and our planet hosts a small population of transient irregular natural satellites or mini-moons that may have been quasi-satellites before becoming temporarily bound to the Earth (Granvik, Vaubaillon & Jedicke 2012; Bolin et al. 2014)

Here, we show that the recently discovered asteroid 2014 OL$_{339}$ is a quasi-satellite companion to the Earth. The object was originally selected as a co-orbital candidate because of its small relative semimajor axis, $|a - a_{\rm Earth}| \sim 0.0002$ au; N-body calculations are used to confirm its current quasi-satellite engagement with our planet. This paper is organized as follows. In Section 2, we briefly outline our numerical model. Section 3 focuses on 2014 OL$_{339}$. Section 4 reviews the current dynamical status of 164207, 277810 and 2013 LX$_{28}$, using their latest orbital solutions. Section 5 provides a comparative dynamical analysis be-

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tween 2014 OL$_{339}$ and the other three Earth quasi-satellites. Our conclusions are summarized in Section 6.

2   NUMERICAL MODEL

Here, we use N-body calculations to study the librational properties of the principal resonant angle of 2014 OL$_{339}$ with the Earth in order to understand its current dynamical status. As an Earth co-orbital candidate, the key object of study is the oscillation of the difference between the mean longitudes of the object and the Earth or relative mean longitude, λ_r. The mean longitude of an object is given by $\lambda = M + \Omega + \omega$, where M is the mean anomaly, Ω is the longitude of the ascending node and ω is the argument of perihelion (see e.g. Murray & Dermott 1999). An object is co-orbital to the Earth if λ_r oscillates (librates) around a constant value; if λ_r can take any value (circulates) then we have a passing object. If λ_r librates around $0°$, we have the quasi-satellite state; the minor planet orbits the Sun in an approximate ellipse with the same (mean) period as the Earth. However, when viewed in a frame of reference that corotates with the Earth, the quasi-satellite follows a retrograde path around our planet over the course of an orbital period, the sidereal year. In principle, such motion is stabilized by the host planet. The stability of quasi-satellite orbits has been studied by Mikkola et al. (2006) and Sidorenko et al. (2014).

The numerical simulations presented here were completed using a Hermite integration scheme (Makino 1991; Aarseth 2003). The standard version of this direct N-body code is publicly available from the IoA web site[1]. Our model Solar system includes the perturbations by the eight major planets and treats the Earth and the Moon as two separate objects, it also incorporates the barycentre of the dwarf planet Pluto–Charon system and the ten most massive asteroids of the main belt, namely, (1) Ceres, (2) Pallas, (4) Vesta, (10) Hygiea, (31) Euphrosyne, 704 Interamnia (1910 KU), 511 Davida (1903 LU), 532 Herculina (1904 NY), (15) Eunomia and (3) Juno. Relative errors in the total energy at the end of the simulations are $< 1 \times 10^{-15}$. The equivalent error in the total angular momentum is several orders of magnitude smaller. Additional details can be found in de la Fuente Marcos & de la Fuente Marcos (2012b) which also discusses 2002 VE$_{68}$, the first documented quasi-satellite.

Results in the figures have been obtained using initial conditions (positions and velocities referred to the barycentre of the Solar system) provided by the Jet Propulsion Laboratory (JPL) HORIZONS system (Giorgini et al. 1996; Standish 1998) and relative to the JD 245 7000.5 epoch which is the $t = 0$ instant. In addition to the calculations completed using the nominal orbital elements in Table 1, we have performed 75 control simulations for each object with sets of orbital elements obtained from the nominal ones within the accepted uncertainties (up to 6σ) that reflect the observational incertitude in astrometry. In any case, the control orbits start very close to the nominal ones as the Gaussian errors are quite small (see Table 1). The computed set of control orbits follows a normal distribution in the six-dimensional orbital parameter space. The orbital evolution is computed in both directions of time at least for 30 kyr. Integration times are longer for the most dynamically stable objects. For clarity, the figures may display just a fraction of the total simulated time. Only a few representative orbits are displayed in the figures.
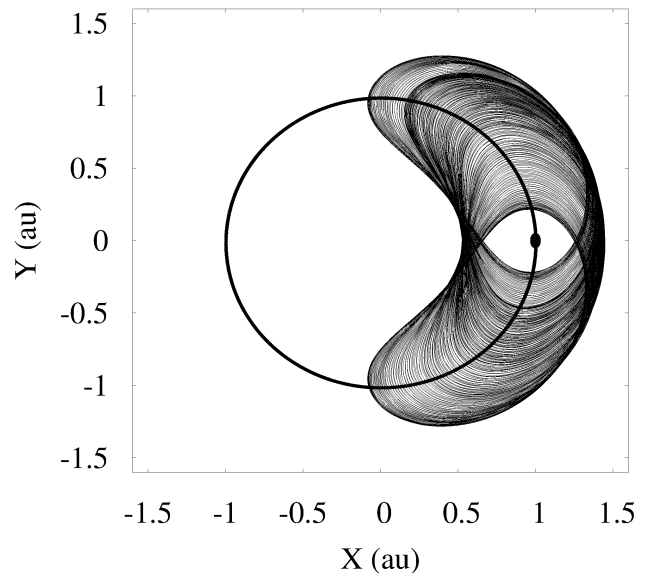
Figure 1. The motion of 2014 OL$_{339}$ over the time range (-150, 150) yr is displayed projected onto the ecliptic plane in a coordinate system rotating with the Earth (nominal orbit in Table 1). The orbit and position of our planet are also indicated. All the investigated control orbits ($\pm 6\sigma$) exhibit the same behaviour within this time frame.

3   ASTEROID 2014 OL$_{339}$, AN ATEN QUASI-SATELLITE

Asteroid 2014 OL$_{339}$ was serendipitously discovered by O. Vaduvescu, V. Tudor, T. Mocnik, V. Dhillon and D. Sahman observing for EURONEAR (Vaduvescu et al. 2008) from La Palma on 2014 July 29 (Vaduvescu et al. 2014). The object was first detected using the 2.5 m Isaac Newton Telescope at an apparent R magnitude of 21.8. The intended target of the program was the Apollo asteroid 2013 VQ$_4$ but 2014 OL$_{339}$ was visible as a streak near the edge of the observed field. With a value of the semimajor axis, a, equal to 0.9994 au, very close to that of our planet (0.9992 au), this Aten asteroid is an NEO moving in an eccentric, $e = 0.46$, and moderately inclined, $i = 10°.19$, orbit that makes it an Earth and Venus crosser, and a Mars grazer. Therefore, its orbit is different from those of the three previously known Earth quasi-satellites (see Table 1): (164207) 2004 GU$_9$, (277810) 2006 FV$_{35}$ and 2013 LX$_{28}$. It is an Aten, not an Apollo, and its eccentricity is the highest of the group which implies that it has the shortest perihelion and the farthest aphelion distances. The source of the Heliocentric Keplerian osculating orbital elements and uncertainties in Table 1 is the JPL Small-Body Database.[2]

Its very small relative semimajor axis, $|a - a_{\mathrm{Earth}}| \sim 0.000$ $197 \pm 0.000\,007$ au (the smallest found so far), makes this object a clear candidate to be an Earth co-orbital. It completes one orbit around the Sun in 364.92 d or 1.00 yr. Its current orbit is based on 27 observations with a data-arc span of 36 d. As expected of a recent discovery, the quality of the orbit of 2014 OL$_{339}$ is at present lower than that of the other minor bodies in Table 1. However, it is similar or even better than the one available when the other objects were recognized as unbound companions to our planet. Asteroid 2014 OL$_{339}$ has $H = 22.6$ mag (assumed $G = 0.15$) or a diameter of 90 to 200 m for an assumed albedo in the range 0.20–0.04. It is,

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Table 1. Heliocentric Keplerian orbital elements of asteroids 2014 OL$_{339}$, (164207) 2004 GU$_9$, (277810) 2006 FV$_{35}$ and 2013 LX$_{28}$, all current quasi-satellites of our planet. Values include the 1σ uncertainty. The orbit of 2014 OL$_{339}$ is based on 27 observations with a data-arc span of 36 d. The orbits are computed at Epoch JD 245 7000.5 that corresponds to 0:00 UT on 2014 December 9 (J2000.0 ecliptic and equinox. Source: JPL Small-Body Database. Data as of 2014 September 15.)

		2014 OL$_{339}$	2004 GU$_9$	2006 FV$_{35}$	2013 LX$_{28}$
Semimajor axis, a (au)	=	0.999 388±0.000 007	1.001 268128±0.000 000003	1.001 27736±0.000 00002	1.001 5884±0.000 0012
Eccentricity, e	=	0.460 67 ±0.000 03	0.136 2649±0.000 0006	0.377 531±0.000 005	0.452 052±0.000 011
Inclination, i (°)	=	10.190 65 ±0.000 5	13.648 35±0.000 05	7.101 62±0.000 13	49.976 1±0.000 3
Longitude of the ascending node, Ω (°)	=	252.223 2±0.001 1	38.675 83±0.000 03	179.541 89±0.000 08	76.681 00±0.000 02
Argument of perihelion, ω (°)	=	289.656 4±0.000 5	280.332 87±0.000 05	170.845 8±0.000 2	345.781 8±0.000 2
Mean anomaly, M (°)	=	215.718 ±0.004	121.353 65±0.000 05	102.135 8±0.000 3	28.143 7±0.000 5
Perihelion, q (au)	=	0.539 00 ±0.000 03	0.864 8304±0.000 0006	0.623 264±0.000 005	0.548 8184±0.000 0011
Aphelion, Q (au)	=	1.459 778 ±0.000 010	1.137 705816±0.000 000004	1.379 29108±0.000 00003	1.454 3585±0.000 0002
Absolute magnitude, H (mag)	=	22.6	21.1	21.7	21.7

therefore, smaller than the previously known Earth quasi-satellites (see Table 1).

The motion of 2014 OL$_{339}$ over the time range (-150, 150) yr as seen in a coordinate system rotating with the Earth projected onto the ecliptic plane is plotted in Fig. 1 (nominal orbit in Table 1). This minor body is an Earth co-orbital currently following a quasi-satellite orbit around our planet (see Mikkola et al. 2006; Sidorenko et al. 2014). Due to its significant eccentricity and in accordance to theoretical predictions (Namouni, Christou & Murray 1999; Namouni & Murray 2000), the libration angle is rather large. The libration centre corresponds to our planet. Asteroid 2014 OL$_{339}$ appears to pursue a precessing kidney-shaped retrograde path when viewed from our planet over the course of a sidereal year. All the investigated control orbits ($\pm6\sigma$) exhibit the same behaviour within the time frame mentioned above.

All the integrated control orbits for 2014 OL$_{339}$ exhibit quasi-satellite libration (λ_r oscillates around 0°) with respect to the Earth at $t = 0$; the object is a quasi-satellite to our planet at a confidence level > 99.99 per cent (see Figs 2 and 3). This co-orbital episode started at least 775 yr ago and it will end 165 yr from now; the duration of the entire quasi-satellite resonance is, in average, approximately 1 kyr (and certainly less than 2.5 kyr), i.e. its current dynamical status is only temporary. The eviction at 165 yr from now coincides with a relatively distant close encounter with our planet at 0.13 au. Prior to the current quasi-satellite episode, the object was probably also co-orbital with our planet, an L$_4$ or L$_5$ Trojan (∼70 per cent) or a horseshoe (∼20 per cent) or, perhaps, a passing object (∼10 per cent) but still in the immediate neighbourhood of Earth's co-orbital region. After leaving its current state, it may become an L$_5$ Trojan (∼10 per cent) or, more likely, a horseshoe librator (∼90 per cent). Due to its significant eccentricity and in accordance to theoretical predictions (Namouni, Christou & Murray 1999; Namouni & Murray 2000), the libration angle as Trojan is greater than the usual value of $\pm60°$, i.e. the libration centre is displaced from the typical equilateral location.

The overall evolution of all the control orbits within the time interval (-775, 165) yr is virtually identical but beyond those time boundaries, the past and future orbital evolution of this object becomes difficult to predict although it remains in the neighbourhood of Earth's co-orbital region for thousands of years. As an example, Fig. 2 displays the short-term dynamical evolution of an orbit arbitrarily close to the nominal one (central panels) and those of two representative worst orbits which are different from the nominal one. The orbit labelled as '-3σ' (left-hand panels) has been

obtained by subtracting thrice the uncertainty from the orbital parameters (the six elements) in Table 1. It has the lowest values of a, e and i at the 3σ level. In contrast, the orbit labelled as '+3σ' (right-hand panels) was computed by adding three times the value of the uncertainty to the orbital elements in Table 1. This trajectory has the largest values of a, e and i (within 3σ). Asteroid 2014 OL$_{339}$ was considerably more stable in the past. It may remain as a co-orbital to our planet switching between the various co-orbital states for many kyr. The values of its semi-major axis (C-panels), eccentricity (D-panels) and inclination (E-panels) remain fairly constant during the entire co-orbital evolution and the object stays well beyond the Hill sphere of our planet (A-panels). The value of its argument of perihelion circulates (F-panels). The results of our calculations show that the true phase-space trajectory followed by this object will diverge exponentially from that obtained from the nominal orbital elements in Table 1 within a relatively short time-scale; its e-folding time is of order of 1 kyr. An additional test for consistency is given in Fig. 3 where the orbital elements have been further modified at the $\pm6\sigma$ level. The short-term dynamical evolution is still consistent with that in Fig. 2 although the object was not co-orbital with our planet a few thousand years into the past. We can certainly state that the probability of this object being a currently active quasi-satellite of our planet is 0.9999966.

4 EARTH QUASI-SATELLITES: A REVIEW

The subject of currently active Earth quasi-satellites has not been revisited recently even if the orbits of those objects recognized as such have been significantly improved in recent times. Here, we provide a brief review of the current dynamical status of (164207) 2004 GU$_9$, (277810) 2006 FV$_{35}$ and 2013 LX$_{28}$, using their latest orbital solutions (see Table 1).

4.1 (164207) 2004 GU$_9$

Asteroid 164207 was discovered by M. Blythe, F. Shelly, M. Bezpalko, R. Huber, L. Manguso, D. Torres, R. Kracke, M. McCleary, H. Stange and A. Milner observing for the Lincoln Near-Earth Asteroid Research (LINEAR) project from Socorro, New Mexico, on 2004 April 13 (Kornos et al. 2004) with the 1.0 m LINEAR telescope. At discovery time its apparent magnitude was 19.6. The orbit of this Potentially Hazardous Asteroid (PHA) of the Apollo class
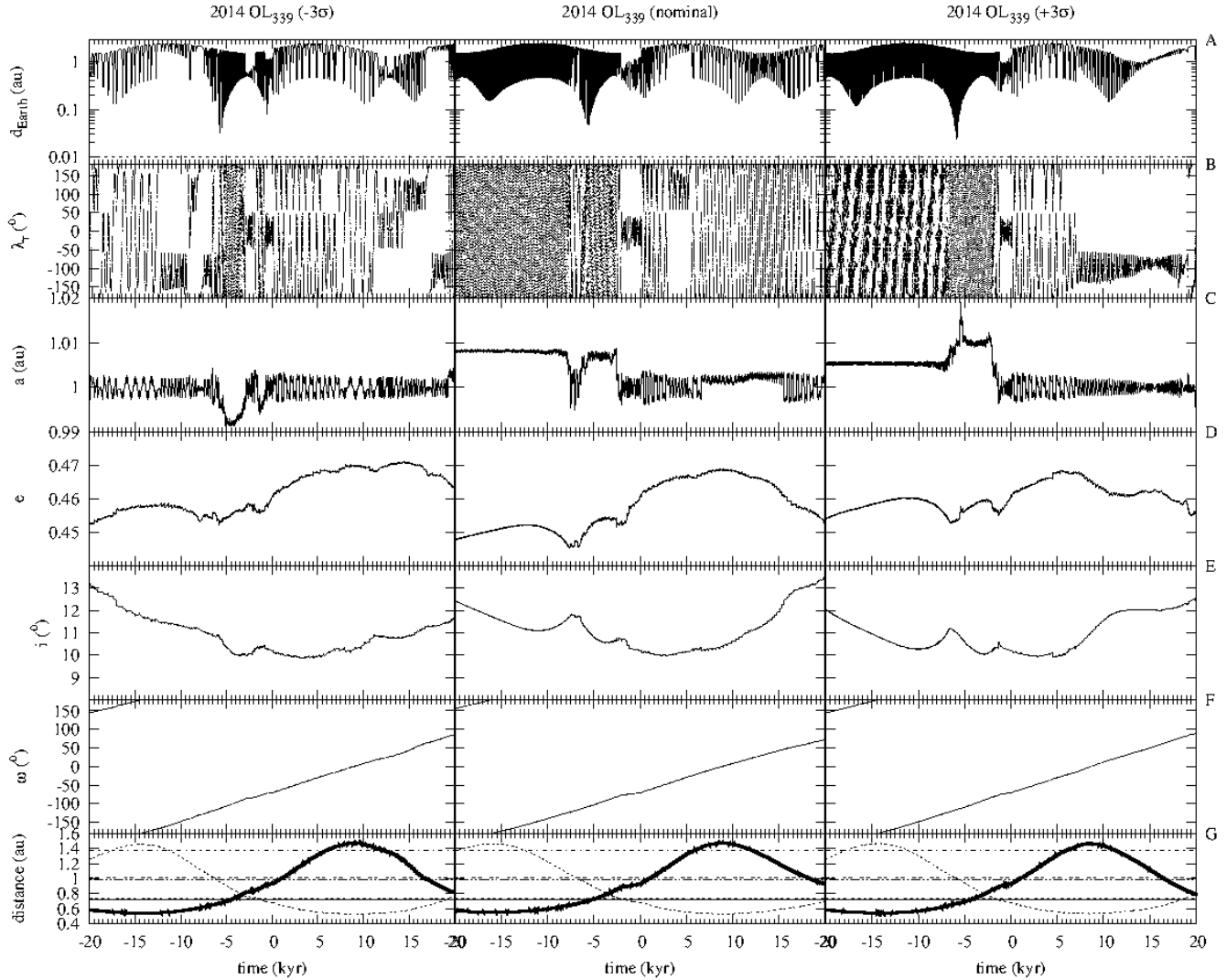
Figure 2. Comparative short-term dynamical evolution of various parameters for an orbit arbitrarily close to the nominal one of 2014 OL$_{339}$ as in Table 1 (central panels) and two representative examples of orbits that are most different from the nominal one (see the text for details). The distance from the Earth (A-panels); the value of the Hill sphere radius of the Earth, 0.0098 au, is displayed. The resonant angle, λ_r (B-panels). The orbital elements a (C-panels), e (D-panels), i (E-panels) and ω (F-panels). The distances to the descending (thick line) and ascending nodes (dotted line) appear in the G-panels. Earth's, Venus' and Mars' aphelion and perihelion distances are also shown.

has a value of the semimajor axis $a = 1.0013$ au. Its orbital eccentricity and inclination are moderate, $e = 0.14$ and $i = 13°.6$. With such an orbit, 164207 always remains in the neighbourhood of the orbit of the Earth–Moon system; no close encounters with other inner planets are possible (see Table 1). Its current orbit is based on 175 observations with a data-arc span of 4 718 d. Besides its orbit, little else is known about 164207: its absolute magnitude has a value of 21.1 mag and its albedo is 0.219 with a diameter of 163 m (Mainzer et al. 2011).

Asteroid 164207 was recognized as a relatively long-lived quasi-satellite companion to the Earth by Connors et al. (2004) and its dynamics was further studied by Mikkola et al. (2006) and Wajer (2010). With the orbit available at the time, these studies concluded that the minor body would remain a quasi-satellite of our planet for several hundred years. Prior to its current dynamical state, 164207 had been a horseshoe librator to the Earth for many thousands of years, its λ_r oscillating around $180°$. Using the latest orbital solution, all the integrated control orbits for 164207 (within 6σ) exhibit

quasi-satellite libration with respect to the Earth at $t = 0$ (see Fig. 4). The historical and future evolution of all the control orbits computed coincide in painting an evolutionary track dotted by multiple quasi-satellite resonant episodes of relatively short-duration, just a few kyr or less (see B-panels, Fig. 4). Most of the time, the object is a horseshoe librator to our planet. Transitions between the two resonant states are not triggered by particularly close encounters with the Earth–Moon system but by the persistent action of other mean motion resonances. Asteroid 164207 orbits the Sun in a near 13:8 resonance with Venus so this planet completes 13 orbits around the Sun in the same amount of time the asteroid completes 8. This fact was already pointed out by Wajer (2010). The timings of the transitions depend strongly on the initial conditions. The orbit of this object cannot be predicted with enough certainty beyond a few thousand years. Its present co-orbital episode started about 450 yr ago and it will end nearly 570 yr from now; the duration of the entire quasi-satellite resonance is, in average, nearly 1 kyr with very little dispersion, i.e. like 2014 OL$_{339}$ its current dynamical
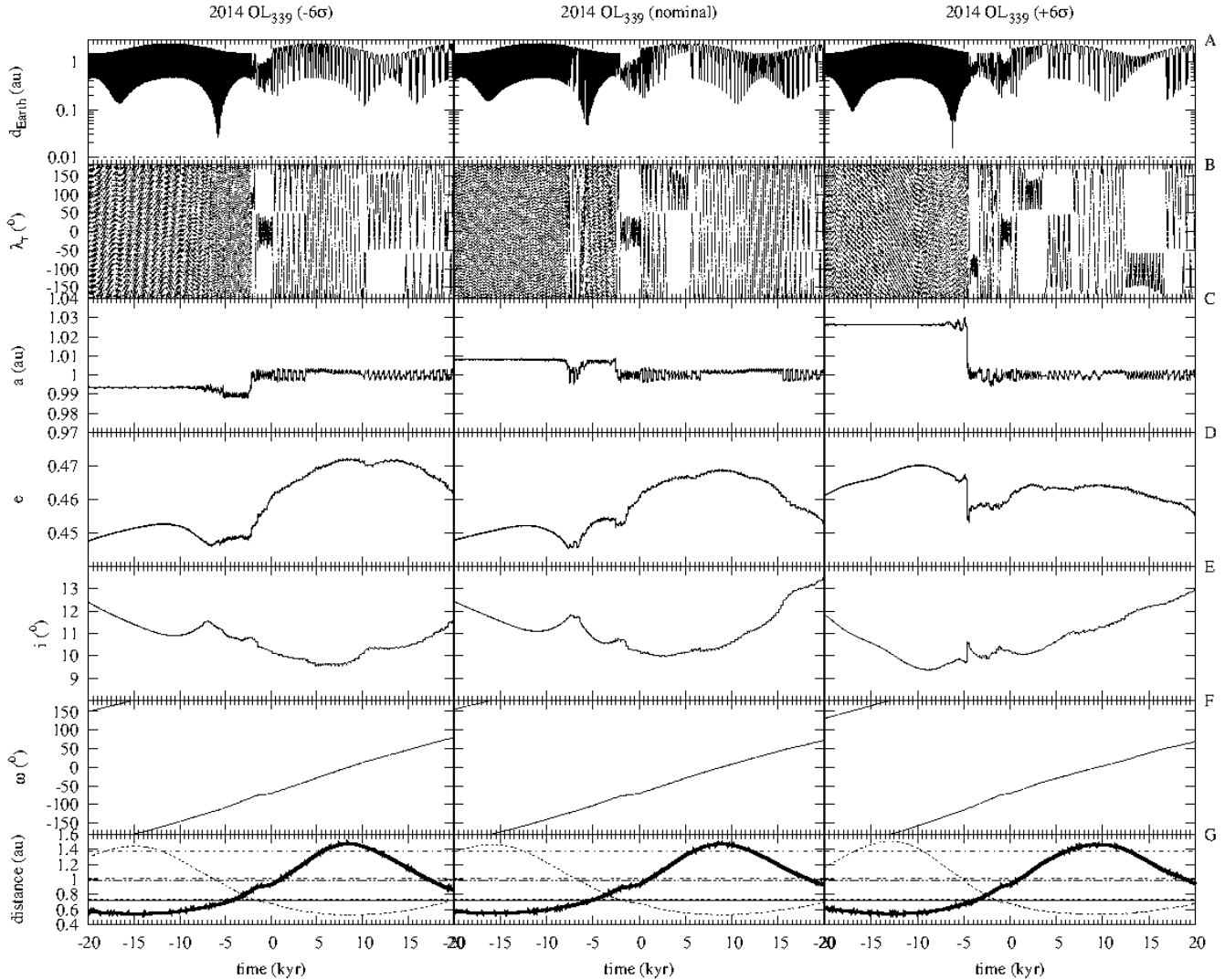
**Figure 3.** Same as Fig. 2 but for $\pm 6\sigma$ deviations.

status is only temporary. Prior to its current engagement as quasi-satellite, this minor body was very probably a horseshoe ($\sim$100 per cent). After leaving its current state, it will return to be a horseshoe librator ($\sim$100 per cent). For this object, horseshoe episodes last in average 4 to 6 kyr. These results are consistent with those from previous studies.

4.2 (277810) 2006 FV$_{35}$

Asteroid 277810 was discovered by J. V. Scotti observing from the Steward Observatory at Kitt Peak for the Spacewatch project on 2006 March 29 (Gilmore et al. 2006). The object was detected using a 0.9 m telescope at an apparent magnitude of 21.0. With a value of the semimajor axis $a = 1.0013$ au, this Apollo asteroid is an NEO moving in an eccentric, $e = 0.38$, and slightly inclined, $i = 7°10$, orbit that makes it cross the orbits of Venus and the Earth–Moon system (see Table 1). Its current orbit is based on 94 observations with a data-arc span of 6 931 d. Although the object has been observed for almost two decades (the first known pre-discovery observations were made on 1995 April 1), little else besides the orbit is known about 277810; its absolute magnitude, $H = 21.7$ (assumed

$G = 0.15$), indicates a diameter in the range 130–300 m for an assumed albedo in the range 0.20–0.04.

Asteroid 277810 was first reported to be a quasi-satellite of our planet by Wiegert et al. (2008). Its dynamics was further studied by Wajer (2010) who found that it will remain in its present quasi-satellite state for more than 10 kyr. Our calculations (see Fig. 5) confirm that 277810 is experiencing at present a quasi-satellite resonant episode. The object is currently far more stable than 164207. In contrast with the previous object, 277810 rarely follows a horseshoe path and Trojan episodes are far more common. In Fig. 5, B-panels, we observe that the relative mean longitude can librate around $60°$, then the object is called an L_4 Trojan, or around -$60°$(or $300°$), then it is an L_5 Trojan. In this case, the timings of the transitions coincide with relatively distant –beyond the Hill radius of our planet (0.0098 au)– close encounters with the Earth–Moon system. Its current co-orbital episode started at least 8 kyr ago and it will end about 3 kyr from now; the duration of the entire quasi-satellite resonance is, in average, approximately 18 kyr (and certainly less than 22 kyr), i.e. its current dynamical status is still temporary. Prior to the current quasi-satellite episode, the object was probably also co-orbital with our planet, a horseshoe ($\sim$90
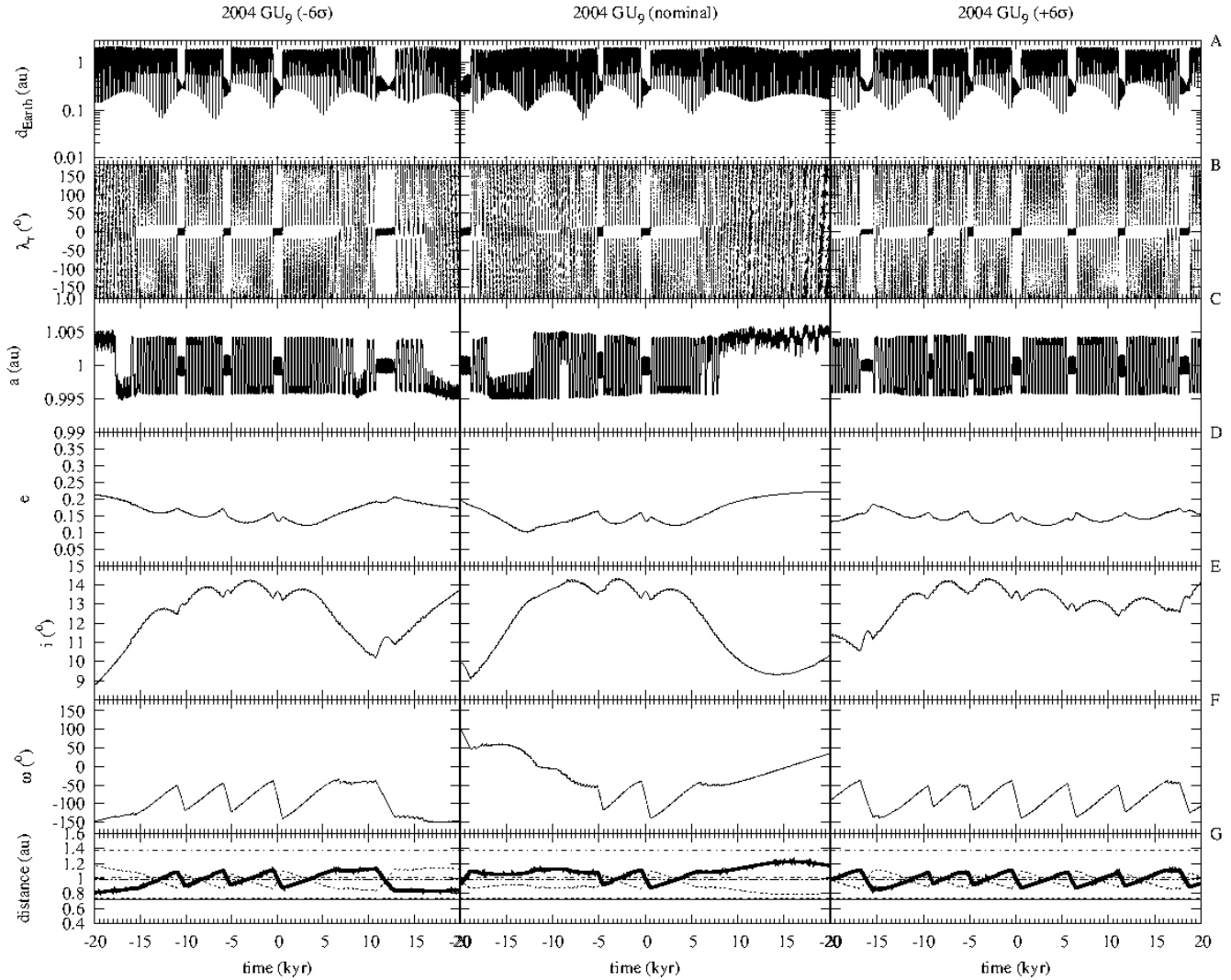
Figure 4. Same as Fig. 3 but for (164207) 2004 GU$_9$.

per cent) or, perhaps, a passing object ($\sim$10 per cent) but still very close to Earth's co-orbital region. After leaving its current state, it may become a passing object ($\sim$10 per cent) or, more likely, an L_5 Trojan ($\sim$90 per cent).

4.3   2013 LX$_{28}$

Asteroid 2013 LX$_{28}$ was discovered by N. Primak, A. Schultz, S. Watters and T. Goggia observing for the Pan-STARRS 1 project from Haleakala on 2013 June 12 (Bressi et al. 2013). The object was first observed using an 1.8 m Ritchey-Chretien telescope at an apparent magnitude of 20.7. With a value of the semimajor axis a = 1.0016 au, this Apollo asteroid is a NEO moving in a rather eccentric, $e = 0.45$, and highly inclined, $i = 50.0°$, orbit that makes it cross the orbits of Venus and the Earth–Moon system, grazing that of Mars and almost that of Mercury. Its current orbit is based on 26 observations with a data-arc span of 349 d. As a recent discovery, little else besides its orbit is known about this object; its absolute magnitude, $H = 21.7$ (assumed $G = 0.15$), suggests a diameter in the range 130–300 m for an assumed albedo in the range 0.20–0.04.

The object was proposed as a Kozai-resonating Earth quasi-satellite by Connors (2014), who pointed out its remarkable stability.

Once an object is trapped in a 1:1 mean motion resonance and depending on its relative energy with respect to the host planet (Hénon 1969), it can describe any of the three main orbit types: quasi-satellite, tadpole or horseshoe. Compound states are also possible in which the object may librate around 0° with an amplitude > 180° encompassing L_4 and L_5 (compound quasi-satellite-tadpole orbit), asymmetric horseshoe orbits (horseshoe-quasi-satellite orbiters) in which the libration amplitude > 270°, encompassing the planet, and a few other combinations (see, e.g., Namouni 1999; Namouni, Christou & Murray 1999). These are typical of objects moving in high-eccentricity, high-inclination orbits and this is what is observed in Fig. 6. Although 2013 LX$_{28}$ is neither a quasi-satellite (see Fig. 6, B-panels) nor a Kozai-resonating body (see Fig. 6, F-panels) in strict sense; λ_r librates around 0° with amplitude > 120° and ω does not librate (or, at least, does not complete a Kozai cycle) just remains relatively close to 0° during the entire compound quasi-satellite-tadpole episode. When 2013 LX$_{28}$ leaves the 1:1 mean motion resonance or before entering it, its argument of perihelion is no longer close to 0°. This behaviour is fully consis-

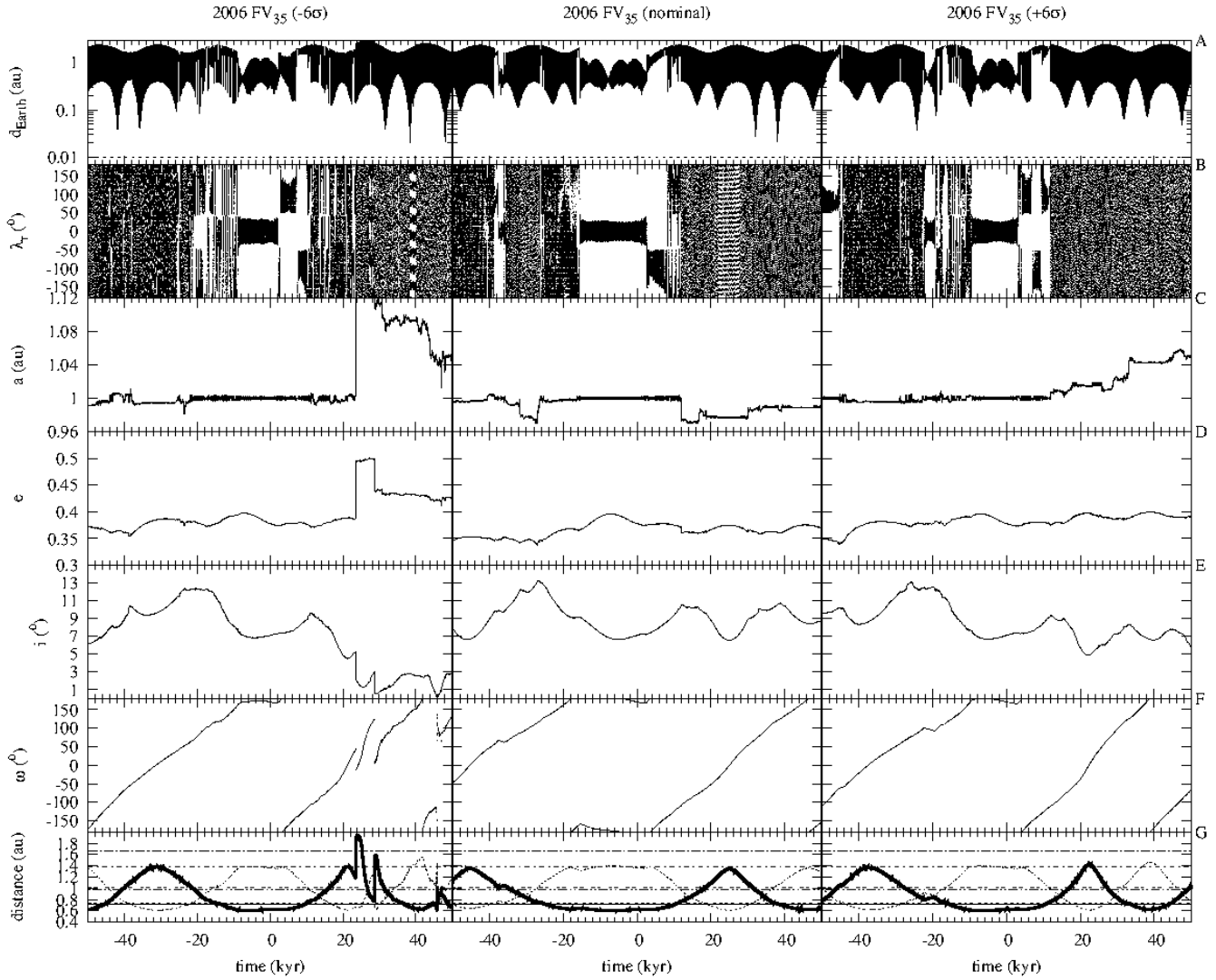**Figure 5.** Same as Fig. 3 but for (277810) 2006 FV$_{35}$.

tent across the set of simulations. Its current co-orbital episode with our planet began at least 5.5 kyr ago and it will end about 16–30 kyr from now; the duration of the entire compound quasi-satellite resonance is, in average, approximately 35 kyr (and certainly less than 45 kyr), i.e. its current dynamical status is also temporary. However, its compound resonant state changes a few times during that time frame, the libration amplitude varies although λ_r still librates around 0°. Prior to the current quasi-satellite episode, the object was probably also co-orbital with our planet, an L_4 Trojan (∼50 per cent) or, perhaps, a passing object (∼50 per cent) but still very close to Earth's co-orbital region. After leaving its current state, it may become a passing object (∼50 per cent) or an L_5 Trojan (∼50 per cent). These Trojan episodes last nearly 10 kyr and are rather asymmetric due to the high-eccentricity, high-inclination orbit.

5 COMPARATIVE DYNAMICAL EVOLUTION OF KNOWN EARTH QUASI-SATELLITES

Figure 7 displays the comparative evolution of the osculating orbital elements and other parameters of interest of all the known

Earth quasi-satellites (nominal orbits in Table 1). It is clear that this group of objects is, dynamically speaking, very heterogeneous. In particular, three objects exhibit Kozai-like dynamics (see F-panels), see Kozai (1962) and Namouni (1999) for technical details: the argument of perihelion of (164207) 2004 GU$_9$ oscillates around -90°, the one of (277810) 2006 FV$_{35}$ librates around 180°, and that of 2013 LX$_{28}$ remains around 0°. The argument of perihelion of 2014 OL$_{339}$ circulates. Some Venus co-orbitals (see e.g. de la Fuente Marcos & de la Fuente Marcos 2013a; de la Fuente Marcos & de la Fuente Marcos 2014) also exhibit Kozai-like dynamics (see Fig. 4, F-panels, in de la Fuente Marcos & de la Fuente Marcos 2014). In particular, the value of the argument of perihelion of 2002 VE$_{68}$ (also a quasi-satellite) remains close to zero during its entire quasi-satellite evolution. For eccentric co-orbitals, this type of resonance provides a temporary effective protection mechanism against close encounters with the host planet: the Earth for 2013 LX$_{28}$ and Venus for 2002 VE$_{68}$. In this case, the nodes are located at perihelion and at aphelion, i.e. away from the host planet (see e.g. Milani et al. 1989).

Asteroid 2014 OL$_{339}$ is an Aten, the other three confirmed quasi-satellites are Apollos although the reason for the absence of
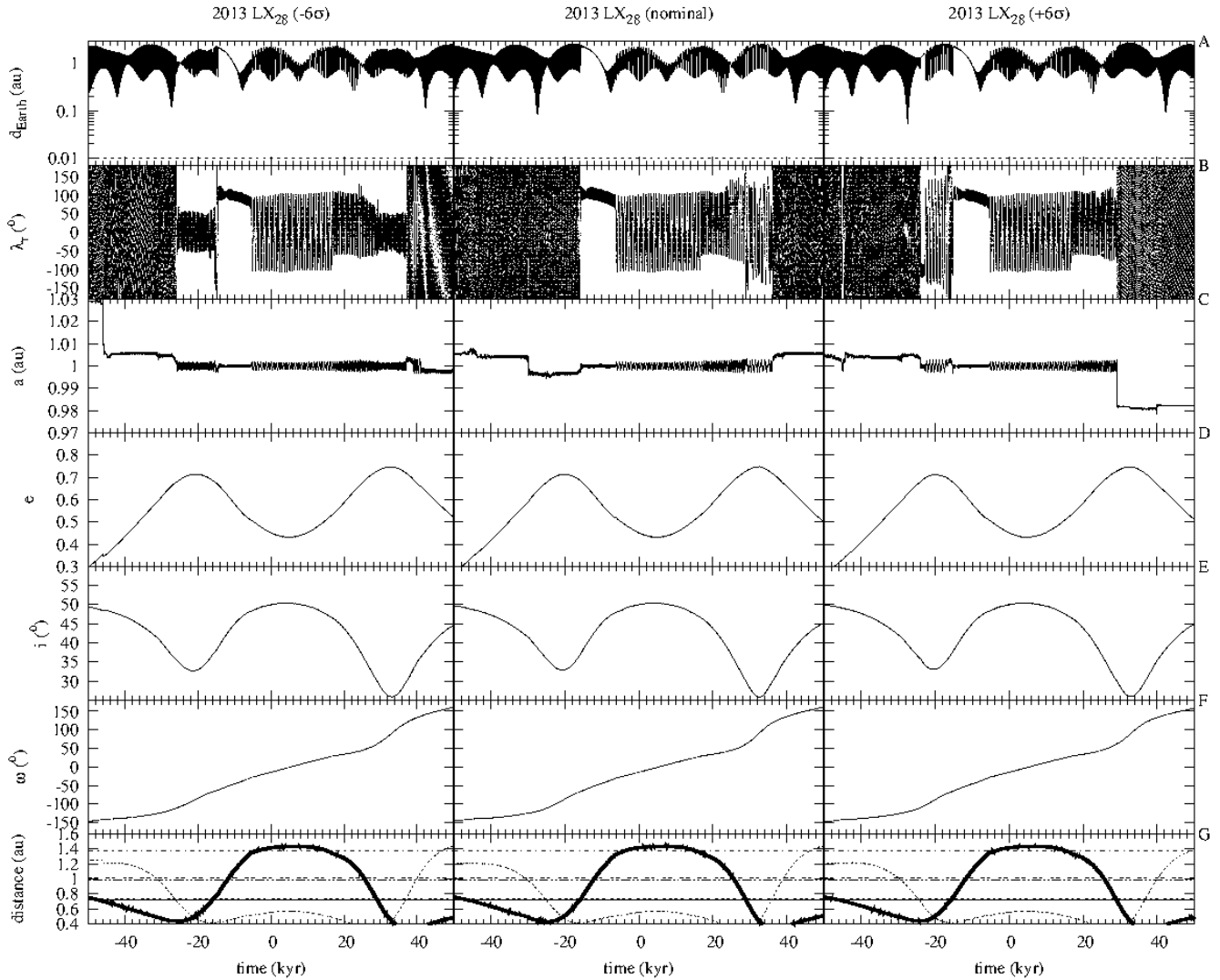
Figure 6. Same as Fig. 3 but for 2013 LX$_{28}$.

the Kozai resonance in the case of 2014 OL$_{339}$ is not this but its relatively large eccentricity. For an object following an inclined path, close encounters with major planets are only possible in the vicinity of the nodes. The distance between the Sun and the nodes is given by $r = a(1 - e^2)/(1 \pm e\cos\omega)$, where the '+' sign is for the ascending node and the '-' sign is for the descending node. The positions of the nodes are plotted in the G-panels of Fig. 7. The descending node of 2014 OL$_{339}$ is close to the orbit of the Earth, its ascending node is near Venus. In contrast, both nodes of 164207 are currently near the Earth, the ascending node of 277810 is perturbed by Mars and the descending one is relatively free from perturbations by Venus; the descending node of 2013 LX$_{28}$ is perturbed by Mars and its ascending one is also relatively free from perturbations by Venus. The Kozai resonance is effective in protecting the paths of 277810 and 2013 LX$_{28}$ against close encounters with the Earth–Moon system as their nodes are away from it, stabilizing their orbits but makes the orbit of 164207 rather unstable. Here, the libration occurs at ω = -90°, not 0° or 180°. Under these circumstances, aphelion and perihelion always occur away from the ecliptic plane. A common feature of the orbital evolutions of 164207 and 2014 OL$_{339}$ is in their enhanced instability when compared to the

other two. This translates into relatively frequent episodes in which we observe switching between resonant states. Transfers between tadpole, horseshoe and quasi-satellite orbits are triggered by close encounters with the inner planets and those are the result of the libration of the nodes (Wiegert, Innanen & Mikkola 1998). Asteroids 277810 and 2013 LX$_{28}$ do not exhibit Kozai-like dynamics outside the time frame in which they are quasi-satellites.

Although there are no two Earth quasi-satellites alike, the closest dynamical relative to 2014 OL$_{339}$ is 164207. It also stays as an Earth quasi-satellite for about 1 kyr (see Fig. 7, second column, panel G) which is consistent with previous results presented by Wajer (2010). It was a horseshoe librator prior to its capture as quasi-satellite and it will return to that resonant state after its eviction. Figure 7 shows that only the Earth-Moon system plays a significant role in destabilizing its orbit; contrary to previous results in Wajer (2010), Venus does not appear to play a significant role in the current dynamical evolution of this object. The orbits of 164207 and 2014 OL$_{339}$ can only be accurately calculated for a few hundred years forward and backward in time. In sharp contrast, 277810 remains in the quasi-satellite state for a long period of time. Our calculations agree reasonably well with those of Wajer
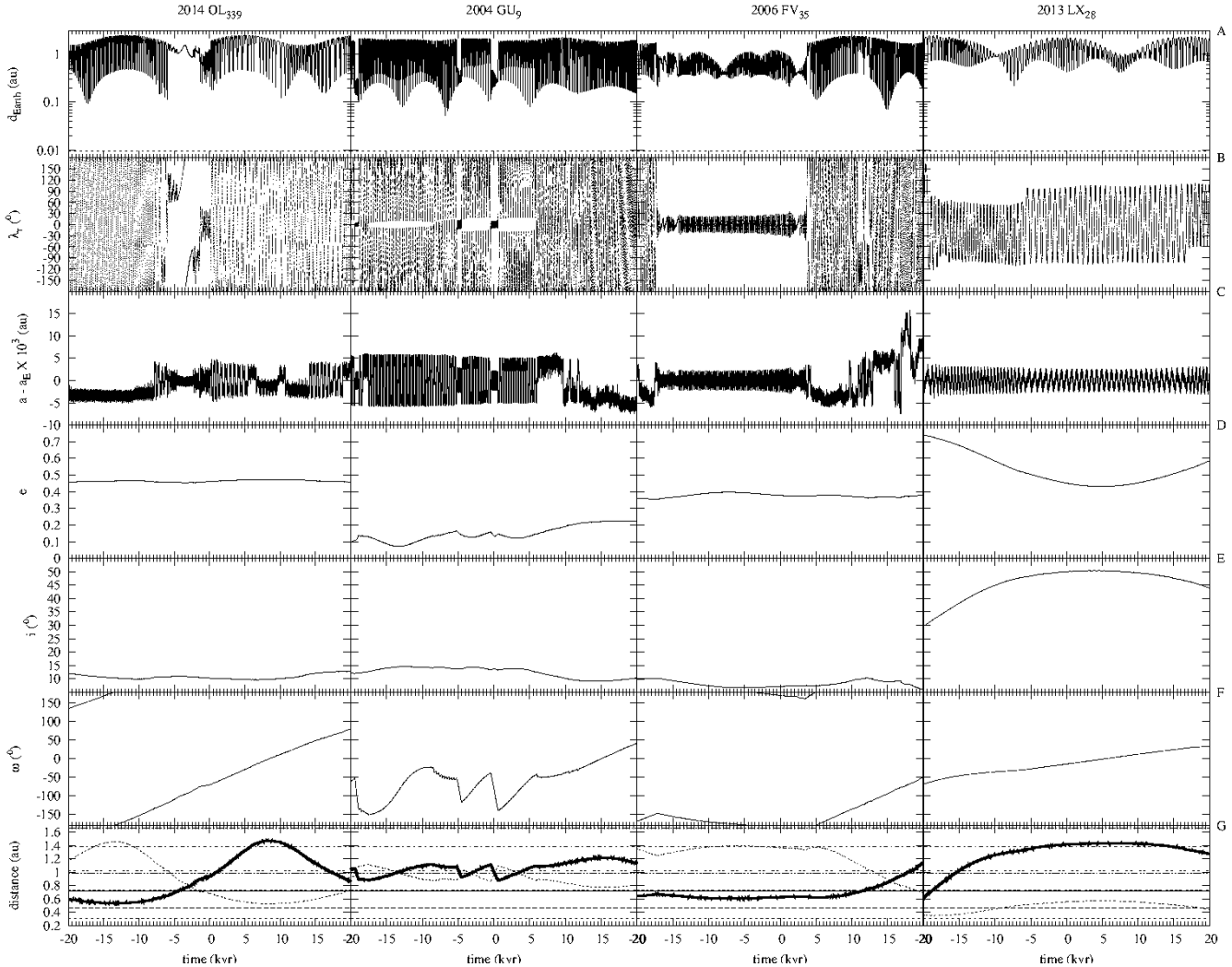
Figure 7. Comparative dynamical evolution of various parameters for the four known Earth quasi-satellites (nominal orbits as in Table 1). The distance from the Earth (panel A); the value of the Hill sphere radius of the Earth, 0.0098 au, is displayed. The resonant angle, λ_r (panel B) for the nominal orbit in Table 1. The orbital elements $a - a_{\text{Earth}}$ (panel C), e (panel D), i (panel E) and ω (panel F). The distances to the descending (thick line) and ascending nodes (dotted line) appear in panel G. Mars', Earth's, Venus' and Mercury's aphelion and perihelion distances are also shown.

(2010), the object has remained in its current state for more than 15 kyr and it will remain there for a few thousand more years. Discrepancies with Wajer (2010) could be the result of using updated orbits and different physical models. Chaotic orbits are not only sensitive to changes in the initial conditions but also to different dynamical models. Although Connors (2014) classifies 2013 LX$_{28}$ as quasi-satellite, this is incorrect in strict sense because its orbit is hybrid. It is a persistent co-orbital companion to the Earth that follows a compound quasi-satellite-tadpole orbit that encloses Earth's Lagrangian points L$_5$ and L$_4$, as well as the Earth itself (see e.g. Namouni 1999; Namouni, Christou & Murray 1999). In principle, close encounters are possible with Mercury, Venus, the Earth and Mars but the asteroid is temporarily protected against close approaches by a Kozai-like resonance with Jupiter. Its dynamics is somewhat similar to that of the well studied Apollo asteroid 10563 Izhdubar (1993 WD) although the argument of perihelion of this object librates around 90° (see Christou 2000b) not 0°. Even if not strictly a quasi-satellite, 2013 LX$_{28}$ is the most stable of the group with a most probable duration of its current state in the range of 35 to 45 kyr.

6 CONCLUSIONS

In this paper we have identified yet another Earth quasi-satellite, 2014 OL$_{339}$. Its dynamical status is temporary and it is not expected to last more than 1 to 2 kyr as this object is one of the most unstable known Earth quasi-satellites; its e-folding time is ∼1 kyr. In the Solar system and among the terrestrial planets, the Earth has the largest number of detected quasi-satellites with four; this is likely to be the result of observational bias, though. A comparative analysis of the short-term dynamical evolution of these objects shows that they are, dynamically speaking, very heterogeneous although three objects exhibit Kozai-like dynamics. The identification of Kozai librators among members of the NEO population is not new (see e.g. Michel & Thomas 1996; de la Fuente Marcos & de la Fuente Marcos 2013b). This indicates that the Kozai resonance plays a significant role in the orbital evolution of many Earth quasi-satellites and also in the chain of events that drives them into this particular resonance and away from it. In this context, 2014 OL$_{339}$ is an outlier as it is the only currently known Earth quasi-satellite not to be submitted to a Kozai resonance. Given their current orbits,

none of the objects discussed here may impact our planet within the next few hundred –(164207) 2004 GU_9 and 2014 OL_{339}– or even several thousand –(277810) 2006 FV_{35} and 2013 LX_{28}– years. Although these four objects are currently experiencing quasi-satellite episodes within the 1:1 mean motion resonance with the Earth, their dynamical contexts are quite different hinting at a richer picture of the quasi-satellite state than conventionally portrayed, with multiple pathways to the same resonant phase. The diverse dynamical histories found for the members of this group make a common origin for any pair of them rather unlikely.

In this work, relativistic terms and the role of the Yarkovsky and Yarkovsky–O'Keefe–Radzievskii–Paddack (YORP) effects (see e.g. Bottke et al. 2006) have been ignored. The non-inclusion of these effects has no impact on the evaluation of the present dynamical status of the minor bodies studied here but may affect predictions regarding their future evolution and dynamical history. In particular, the Yarkovsky effect may have a role on the medium- and long-term evolution of objects as small as the minor bodies discussed here. Proper modelling of the Yarkovsky force requires knowledge on the physical properties of the objects involved (for example, rotation rate, albedo, bulk density, surface conductivity, emissivity) which is not the case for these minor bodies. Perturbational effects arising from the co-orbital evolution with our planet may render these non-gravitational effects negligible, though.

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