Horseshoe Co-orbitals of Earth: Current Population and New Candidates

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ABSTRACT
Most co-orbital objects in the Solar system are thought to follow tadpole-type orbits, behaving as Trojans. However, most of Earth’s identified co-orbitals are moving along horseshoe-type orbits. The current tally of minor bodies considered to be Earth co-orbitals amounts to 18; of them, 12 are horseshoes, five are quasi-satellites, and one is a Trojan. The semimajor axis values of all these bodies librate between 0.983 au and 1.017 au. In this work, we have studied the dynamical behaviour of objects following orbits with semimajor axis within this range that may be in a 1:1 mean-motion resonance with Earth. Our results show that asteroids 2016 CO246, 2017 SL16, and 2017 XQ60 are moving along asymmetrical horseshoe-type orbits; the asteroid 2018 PN22 follows a nearly symmetric or regular horseshoe-type orbit. Asteroids 2016 CO246, 2017 SL16, and 2017 XQ60 can remain in the horseshoe co-orbital state for about 900 yr, 3300 yr and 2700 yr, respectively. Asteroid 2018 PN22 has a more chaotic dynamical behaviour; it may not stay in a horseshoe co-orbital state for more than 200 yr. The horseshoe libration periods of 2016 CO246, 2017 SL16, 2017 XQ60, and 2018 PN22 are 280, 255, 411, and 125 yr, respectively.

Key words: celestial mechanics – asteroids: general – methods: numerical — minor planets, asteroids: individual: 2016 CO246 — asteroids: individual: 2017 SL16 — asteroids: individual: 2017 XQ60 — asteroids: individual: 2018 PN22

1 INTRODUCTION
Co-orbitals are in a 1:1 mean-motion resonance with the host body; they are classified in 3 different classes according to the shape of the orbit: horseshoe (HS), quasi-satellite (QS) or Trojan following a tadpole path (TP). In the Solar system, the HS-type orbits are less common than the TP-type orbits (Christou & Asher 2011). The current tally of known co-orbitals in the Solar system amounts to over 7,000 (JPL’s SBDB1); the majority of them are Jupiter Trojans (de la Fuente Marcos & de la Fuente Marcos 2014b). However, most known Earth co-orbitals (12 out of 18) are in the HS co-orbital state (de la Fuente Marcos & de la Fuente Marcos 2014b). Five of the Earth co-orbitals follow QS-type orbits, and only one asteroid (2010 TK7) follows a TP-type orbit.

In addition to these, there are transitions between the existing HS and QS co-orbitals. Three of the QS-type Earth co-orbitals (2004 GU9, 2006 FV35, 2016 HO3) and five of the HS-type Earth co-orbitals (2001 GO2, 2002 AA29, 2003 YN107, 2015 SO2, 2015 YA) show repeated transitions between QS and HS type orbits over time (Brasser et al. 2004; de la Fuente Marcos & de la Fuente Marcos 2013b). This repetitive orbit-type transition is theorized by Namouni (1999) for the first time has been discussed in detail in various papers for different asteroids (Connors et al. 2002; Brasser et al. 2004; Wajer 2009, 2010). These asteroids spend most of their co-orbital lifetime in HS co-orbital state. As a natural consequence of this behaviour, statistically, the HS-type co-orbital population of those asteroids that show HS-QS transitions can be expected to appear more frequently than the pure QS-type state at any given moment during their co-orbital lifetime.

A plausible explanation for the relative difference of abundance of HS versus TP-type orbits for Earth co-orbitals has been offered by Zhou et al. (2019). The chaotic motion in the inner Solar system changes the secular frequencies of the inner planets. This change is known as the frequency drift of the inner planets. The TP orbits are more sensitive to this drift motion of secular frequencies than the HS ones. Consequently, regarding the inner planets except for Mars, asteroids cannot survive in a Trojan co-orbital state for a long period of time, but they can if they follow HS-type orbits.

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orbits. However, this is not the case for Mars Trojans. To date, there have been identified nine Trojans of Mars, some of which were found in long-term stable orbits (Christou 2013; Ćuk et al. 2015; Christou et al. 2020).

The primary sources of Earth co-orbitals are thought to be the various regions of the main-belt as in the case of non-co-orbital near-Earth asteroids (NEAs) (Morais & Morbidelli 2002; Galianazzo & Schwarz 2014). However, it has been shown recently by Pokorný & Kuchner (2019) using numerical simulations, that primordial Venus co-orbitals could exist. It was also showed that some Mars Trojans can be primordial bodies (Connors et al. 2005; de la Fuente Marcos & de la Fuente Marcos 2013a). Similarly, a primordial co-orbital population may be possible for Earth. If such primordial members among Earth co-orbitals are possible, they should be moving along orbits that are less-sensitive to frequency drift. Therefore, the primordial co-orbitals of Earth are more likely to exist following HS-type orbits. This possibility increases the attractiveness of the study of HS co-orbitals of Earth.

In the last three years, approximately 35 new asteroids have been found following orbits whose orbital periods are very close to Earth’s (semimajor axes in the range 0.99 au < a < 1.01 au). Over the last 35 years, this number has reached 100 and although many of them do not display co-orbital dynamical behaviour of any kind, 18 have been shown to be trapped in a 1:1 mean-motion resonance with Earth. In particular, the low-eccentricity ones among these bodies may be members of a resonant family defined in de la Fuente Marcos & de la Fuente Marcos (2013b) that is a subgroup of the proposed near-Earth asteroid belt (Rabinowitz et al. 1993; Brasser & Wiepert 2008).

In this work, we have studied near-Earth asteroids moving along orbits with semimajor axes in the range 0.983 au < a < 1.017 au to find among them those that are candidates to be trapped in 1:1 mean-motion resonance with Earth. Six objects, namely 2016 CO36, 2017 SL16, 2017 XQ90, 2018 PN22, 2018 AN2 and 2018 XW5 moving along HS-type orbits have been identified. The orbits of asteroids 2016 CO36, 2017 SL16, 2017 XQ90 and 2018 PN22 with relatively good orbital solutions have been studied in detail. As a result of the dynamical analyses of their orbital evolutions, these asteroids can be classified as HS co-orbitals of Earth. Section 2 includes a short review about the already known HS co-orbitals of Earth. In Sect. 3, the initial conditions, and numerical methods used are outlined. Section 4 presents and discusses the results. Section 5 summarizes the conclusions.
### Table 1. Horseshoe Co-orbitals of Earth (Epoch: JD 2458600.5 (2019-Apr.-27.0) TDB (J2000.0 ecliptic and equinox). Source: JPL’s SSDG SBDB)

| Name            | $a$ (au)                  | $e$                  | $i$ (°)              | $\Omega$ (°)           | $\omega$ (°)         | $H$ (mag) | MOID Condition | Code |
|-----------------|---------------------------|----------------------|----------------------|------------------------|----------------------|-----------|----------------|------|
| (3753) Cruithne | 0.99780415394 ± 4.86 x 10^{-5} | 0.51489615 ± 4.86 x 10^{-5} | 1.13 ± 10^{-3} | 126.227503 ± 8.78 x 10^{-5} | 43.800079 ± 8.76 x 10^{-5} | 15.6 | 0.07120 | 0 |
| (54509) YORP    | 1.00589555555 ± 2.60 x 10^{-3} | 0.22996766 ± 1.42 x 10^{-3} | 1.50 ± 10^{-4} | 278.339970 ± 6.70 x 10^{-5} | 28.9371158 ± 6.43 x 10^{-5} | 22.7 | 0.00276 | 7 |
| 2001 GO2       | 1.0686417 ± 3.07 x 10^{-3} | 0.168236 ± 6.09 x 10^{-4} | 1.19 ± 10^{-2} | 193.54071 ± 1.25 x 10^{-3} | 265.4661 ± 2.28 x 10^{-2} | 24.3 | 0.00392 | 3 |
| 2002 AA29      | 0.9925404414 ± 2.41 x 10^{-3} | 0.01302163 ± 2.00 x 10^{-4} | 5.53 ± 10^{-3} | 106.365320 ± 2.19 x 10^{-4} | 101.901700 ± 4.35 x 10^{-4} | 24.1 | 0.01184 | 0 |
| 2003 YN107     | 0.986858239 ± 3.59 x 10^{-3} | 0.01943470 ± 2.11 x 10^{-4} | 2.63 ± 10^{-3} | 264.400097 ± 6.77 x 10^{-5} | 87.687653 ± 1.10 x 10^{-4} | 26.5 | 0.00504 | 1 |
| 2005 JY26      | 1.0107976 ± 1.02 ± 10^{-3} | 0.0889891 ± 1.79 x 10^{-4} | 1.54 ± 10^{-4} | 43.66551 ± 7.92 x 10^{-4} | 273.6480 ± 1.79 x 10^{-2} | 28.4 | 0.00011 | 3 |
| 2010 SO16      | 1.00316220453 ± 8.89 x 10^{-3} | 0.075402873 ± 9.99 x 10^{-4} | 2.47 ± 10^{-4} | 40.384407 ± 2.96 x 10^{-5} | 109.0117369 ± 6.34 x 10^{-5} | 20.5 | 0.02968 | 0 |
| 2013 BS45      | 0.997353720 ± 1.44 x 10^{-3} | 0.08374979 ± 3.30 x 10^{-4} | 3.74 ± 10^{-3} | 83.364994 ± 4.33 x 10^{-4} | 150.694382 ± 4.58 x 10^{-4} | 25.9 | 0.01147 | 0 |
| 2015 SO2       | 0.9956965867 ± 3.14 x 10^{-3} | 0.10874469 ± 7.64 x 10^{-4} | 7.62 ± 10^{-3} | 182.773871 ± 2.19 x 10^{-4} | 291.437237 ± 4.43 x 10^{-4} | 23.9 | 0.01089 | 1 |
| 2015 XX16      | 1.00145825 ± 1.97 ± 10^{-3} | 0.1848235 ± 1.51 x 10^{-4} | 4.26 ± 10^{-3} | 256.4757755 ± 7.38 x 10^{-4} | 282.800358 ± 1.05 x 10^{-4} | 27.4 | 0.01500 | 0 |
| 2015 YA        | 0.99583149 ± 9.99 x 10^{-4} | 0.279672 ± 2.22 x 10^{-4} | 8.38 ± 10^{-4} | 255.01138 ± 3.31 x 10^{-3} | 83.6267 ± 1.62 x 10^{-2} | 27.4 | 0.00355 | 6 |
| 2015 YQ1       | 1.0039842 ± 1.58 ± 10^{-3} | 0.40406 ± 2.14 x 10^{-4} | 1.85 ± 10^{-3} | 88.860853 ± 3.22 x 10^{-4} | 111.8716 ± 1.71 x 10^{-2} | 28.0 | 0.00061 | 6 |

**Figure 1.** Libration period versus minimum distance to Earth for HS co-orbitals of Earth. The blue line corresponds to a linear fit for those whose eccentricity value is less than 0.2 (3753) Cruithne, (54509) YORP, 2015 YQ1, 2017 XQ60, and 2018 XW2 are excluded.

Horseshoe Co-orbitals of Earth: New Candidates

of the objects analysed in this work, is in the Apollo class for Epoch 2017-Jan.13.0 and in the Aten class for Epoch 2018-Sep.10.

It is relatively frequent for some asteroids to switch between Apollo class and Aten class membership. However, this is usually caused by the chaotic orbital movements of asteroids. The situation mentioned here is the result of the almost-periodic motion of the objects as a consequence of being trapped in a 1:1 mean-motion resonance with Earth.

According to the classical definition of co-orbital motion (see Murray & Dermott 1999), two objects that are co-orbital candidates have to share the value of the semimajor axis as well as to have a relative mean longitude that librates around certain particular values. The mean longitude of an object is $L = \Omega + \omega$, where $M$ is the mean anomaly, $\Omega$ is the longitude of the ascending node and $\omega$ is the argument of perihelion. The relative mean longitude is defined as the difference between the mean longitude of the host body and the mean longitude of the object. If it librates around $0^\circ$, the object is in the quasi-satellite co-orbital state, if it librates around $60^\circ$, the object is called an $L_4$ Trojan, when it librates around $300^\circ$ (or $-60^\circ$), it is an $L_5$ Trojan, whereas if the libration amplitude is larger than $180^\circ$ it is called a horse. (Dermott & Murray 1981a; Murray & Dermott 1999; Morais & Morbidelli 2002; Connors et al. 2002). Although objects in co-orbital motion share the semimajor axis and their mean lengths relative to the host body, Earth in this case, oscillate around certain values, i.e. either $0^\circ$, $60^\circ$, or $180^\circ$, their eccentricity and inclination may be very different. Consequently, the asteroids (3753) Cruithne, (54509) YORP (2000 PH$_5$) listed here (Table 1) have very high orbital eccentricities and are thus moving along orbits that are different from that of Earth.

In particular, these bodies can be considered as HS-type co-orbitals of Earth, being in a 1:1 mean-motion resonance with Earth and having as shape of their orbit projected onto the ecliptic plane, from the point of view of a frame of reference that co-rotates with Earth, one that resembles that of an actual horse. This first group of objects is called unusual HS co-orbitals.

The orbits of 2002 AA29, 2003 YN107, (419624) 2010 SO16, (454094) 2013 BS45, and 2015 SO2 are well suited for these objects to be classified as HS-type co-orbitals of Earth in the classical sense. Their eccentricities are quite small. The maximum $e$ value in this group is 0.1087152 which...
belongs to asteroid 2015 SO2. Their relative mean longitude librates with an amplitude larger than 180°, and they are in 1:1 mean-motion resonance with Earth. However, they do not pass between Earth and the Sun in the frame of reference that co-rotates with Earth. Orbits of these objects can be termed nearly-symmetric HS.

There exists a third subgroup of Earth co-orbitals considered to be HS. The orbital eccentricities of these bodies are greater than that of the nearly-symmetric HS and smaller than that of the unusual HSs. In contrast to non-symmetrical HS orbits, the relative mean longitudes of these bodies reach 0°. This implies that the “horns” in the relative orbit shape of the objects are not positioned to hold Earth in between. Therefore, the object crosses twice the minimum distance with Earth in a HS cycle. 2001 GO2, 2015 XX169 and 2006 JY36 are the members of this group. For the orbit of these bodies, as mentioned in de la Fuente Marcos & de la Fuente Marcos (2016b), the asymmetrical HS expression seems to fit.

There are two objects which we have not counted yet in any of these three classes. These objects have been classified as HS in the literature, they are 2015 YA and 2015 YQ1.

Analyses and evaluations of the dynamical evolution of asteroid 2015 YA have been presented by de la Fuente Marcos & de la Fuente Marcos (2016b). The orbital solutions of the 2015 YA were relatively poor at that time. Thus, some statistical approaches were used to assess the dynamical state of the asteroid according to the then nominal parameters. In the above mentioned work, it is stated that the object follows an asymmetrical horseshoe path viewed in a frame of reference that co-rotates with Earth and projected onto the ecliptic plane. Even if the orbital solution of 2015 YA is not still well defined, uncertainties seem to have diminished a little over time. At least, the new nominal orbital parameters produce somewhat different results than the ones mentioned in that paper.

According to the orbital solution that corresponds to the current nominal orbital parameters, 2015 YA stays near Earth’s mean longitude for almost 225 yr. This implies that its orbit follows an asymmetrical quasi-satellite trajectory with respect to Earth. After 225 yr of dynamical evolution, its orbital path starts to show asymmetrical HS features.

Additionally, a similar situation is observed for 2015 YQ1. The orbit is defined as asymmetrical HS in de la Fuente Marcos & de la Fuente Marcos (2016b). While the 2015 YQ1 seems to be an asymmetrical HS according to the calculations made for its current nominal orbital elements, the “horns” of the HS are located behind the L4 point. The object should be classified as unusual HS due to its high $e$ value and irregular $a$ graph.

3 NUMERICAL METHODS AND INITIAL CONDITIONS

It cannot be claimed that a minor body is in co-orbital motion with a host planet simply because its orbital elements have certain particular values. The dynamical evolution of some orbital parameters must be studied by means of forward and backward integrations over a reasonably long amount of time. In particular, the time evolution of $a$ and $\lambda_r$ (mean longitude relative to Earth) provides information about whether the orbit is co-orbital. The orbit is integrated both forward and backward in time; $A_r$ is followed. If the asteroid is in a co-orbital state, $A_r$ librates around ±60° (or ±300°), ±180°, or 0°, and it is classified as tadpole, horseshoe, or quasi-satellite, respectively (de la Fuente Marcos & de la Fuente Marcos 2016a).

Small uncertainties in the orbital elements may cause relatively large differences in the results after a medium or long-term integration due to the chaotic nature of the dynamical evolution. Thus, it is necessary to investigate the effects of small uncertainties on the dynamical evolution of the orbital elements using clones within the framework of a statistical approach. As a result of these statistical analyses, a more reliable result is obtained about the shape and evolution of the orbit. In this way, it is possible to gain a better insight into the orbital stability in the close vicinity of the nominal orbit of the co-orbital candidate.

In the calculation of the probability distribution, a clone must complete at least one HS libration period in backward or forward simulations starting from its current position to be assumed that it is moving along a HS type orbit. The probability of one body being in a co-orbital state is obtained by dividing the number of orbits in this state by the total number of clones. The total probability is therefore only valid for one libration period.

In this work, the MCCM (Monte Carlo using Covariance Matrix) (Bordovitsyna et al. 2001; Avdyushev & Banaschikova 2007; de la Fuente Marcos & de la Fuente Marcos 2012) method is used to produce clone orbits. Through this approach, the effects of the uncertainties of the orbital parameters on other parameters are included in the generated clones.

A model Solar system including the eight known planets, the dwarf planet (1) Ceres, the main-belt asteroids (2) Pallas, (4) Vesta, (10) Hygiea, (31) Euphrosyne and the Moon has been used for the numerical integrations performed with the REBOUND $N$-body integration package (Rein & Liu 2012). This package makes use of a 15th order Gauß-Radau quadrature integration scheme (IAS15 integrator) (Rein & Spiegel 2014). The initial conditions for all large and dwarf planets, minor bodies and the Moon have been obtained using the Jet Propulsion Laboratory’s Solar System Dynamics Group Small-Body Database (JPL’s SSDG SBDB, Giorgini et al. 2001; Giorgini 2011, 2015) and JPL’s Horizons ephemeris system (Giorgini et al. 1996; Standish 1998; Giorgini & Yeomans 1999) for the epoch JD 2458600.5 (2018-Apr-27.0) TDB (Barycentric Dynamical Time).

Some tests were made for known HS co-orbitals of Earth with both MERCURY 6 package (Chambers 1999) with Bulirsch-Stoer integrator and REBOUND package with IAS15 integrator to check the reliability of the results. We got almost the same results for both packages for a few thousand years. However, relative energy error for IAS15 integrator was in machine precision level. Besides, tests were performed using REBOUND package with IAS15 integrator for known HS co-orbitals of Earth and the results were compared with those in the literature. Notable different results were obtained for only two bodies (2015 YA and 2015 YQ1) and they were mentioned in Section 2.

Numerical integration tests showed that the inclusion of dwarf planets and the main-belt asteroids has no significant effect on the results of the dynamical evolution of the mi-

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or bodies studied here within the time-scale of dynamical evolution studied in this research.

The upper and lower limits for the semimajor axis of an asteroid in a 1:1 mean motion resonance with Earth are given as 0.99 au and 1.01 au (Morais & Morbidelli 2002). However, our preliminary studies have shown that the semimajor axis librations for asteroids 2006 JY6 and 2018 PN22 force these limits. Thus, in this study the surveyed part of the orbital parameter space corresponds to a semimajor axis range of 0.983 au < a < 1.017 au, slightly larger than the theoretical limit. At the time of this writing (2019 April 1) there are 239 minor bodies in this semimajor-axis range (source: JPL Small-Body Database Search Engine). We have studied the dynamical evolution of these near-Earth objects and found that the evolution of the nominal orbital parameters of asteroids 2016 CO6, 2017 SL16, 2017 XQ60, 2018 PN22, 2018 AN2 and 2018 XW2 is consistent with them being trapped in a 1:1 mean-motion resonance with Earth and showing dynamical features characteristic of the HS-type dynamical state. Table 2 shows the osculating orbital parameters, absolute magnitudes, and condition codes of the HS co-orbital candidates for Earth. At the moment, the orbital solutions for the asteroids 2018 AN2 and 2018 XW2 are still poor. This implies that their condition codes (uncertainty parameters) are currently high (both 7). If they are not observed again in the next future and at the appropriate positions, their condition codes will stay at the same level for a long time like in the case of 2001 GO2 (Brasser et al. 2004).

4 RESULTS

Here, nominal and clone orbits of asteroids 2016 CO6, 2017 SL16, 2017 XQ60, and 2018 PN22 with low orbital uncertainties have been analysed by numerically integrating their orbits both backward and forward in time. To clarify the uncertainties have been analysed by numerically integrating their conditions both backward and forward in time. To clarify the uncertainties, their condition codes will stay at the same level for a long time like in the case of 2001 GO2 (Brasser et al. 2004).

Figure 2 shows the short-term dynamical evolution of the relevant orbital parameters a, e, i, $\Omega$, $\omega$, d (Earth distance in au), and the Kozai parameter ($\sqrt{1-e^2}\cos i$) for the nominal orbits of 2016 CO6, 2017 SL16, 2017 XQ60, and 2018 PN22 for a time interval of integration that goes from 1000 yr into the past to 1000 yr into the future.

Figures 3, 5, 7, and 8 show the dynamical evolution of the orbital parameters for 2016 CO6, 2017 SL16, 2017 XQ60, and 2018 PN22 with the averages of their clones’ orbital parameters for ±10 000 yr. The clones were produced according to the MCCM method. 1000 different clones have been used for forward and backward integrations. In addition to the relevant orbital parameters, we have also studied the dynamical evolution of the Kozai parameter.

In addition to these, some long-term integrations were performed for 2016 CO6, 2017 SL16, and 2017 XQ60 for 1 Myr using 10 clone orbits for each body. However, small differences between clone orbits started to increase in a few kyr of dynamical evolution. Their dynamical evolutions are chaotic for long term integrations. As a result, semimajor axes of all the clone orbits of 2016 CO6 stayed in the range of 0.992 au to 1.007 au for a duration of 9.91 kyr. For 2017 SL16 the range is 0.990 au to 1.007 au for a duration of 18 kyr, and for 2017 XQ60 the range is 0.994 au to 1.007 au for a duration of 19 kyr.

After that, they began to follow different trajectories. Besides, it should be considered that these are very small bodies and are expected to be more affected by non-gravitational effects in long-term integrations. Therefore, very long-term integrations should also be made using a large number of clones including non-gravitational effects to obtain reasonable results.

4.1 Asteroid 2016 CO6

Asteroid 2016 CO6 was discovered by the Pan-STARRS survey (Kaiser 2004; Kaiser & Pan-STARRS Project Team 2004) on 2016 February 11. The orbit determination of this minor body is based on 42 observations for a data-arc span of 1088 days. The condition code is 0, which indicates that the uncertainty in the calculated orbit is rather small. Asteroid 2016 CO6 is relatively small with an absolute magnitude of 25.8 mag, which suggests a diameter in the range 12-92 m for an assumed albedo in the range 0.60-0.01. The MOID value for Earth is 0.03752 au. However, due to its absolute magnitude, which is less than 22, the object is not in the PHA list.

2016 CO6 is classified as an Aten in ESA’s NEO page and as an Apollo in the JPL Small-Body Database Browser (its semimajor axis is a = 0.99936 au for Epoch JD 2458371.5 (2018-Sept.-10.0) but a = 1.00075 for Epoch JD 2457766.5 (2017-Jan.-13.0)). Both classifications are correct due to the fact that the object switches between Apollo and Aten dynamical classes. It was an Apollo in 2017 but it is a member of the Aten dynamical class currently, and our calculations indicate that it will return to the Apollo dynamical class after 138 yr of dynamical evolution. As we have already mentioned in Section 2, the classification of the object will

| Name | a (au) | e | i (◦) | $\Omega$ (◦) | $\omega$ (◦) | H (mag) | MOID (au) | Condition Code |
|------|--------|---|------|------------|----------|--------|----------|----------------|
| 2016 CO6 | 0.998232064 ± 4.05 × 10⁻⁹ | 0.125630 ± 4.00 × 10⁻⁷ | 6.3271019 ± 1.76 × 10⁻³ | 136.6355805 ± 1.06 × 10⁻³ | 119.4946322 ± 2.61 × 10⁻³ | 25.8 | 0.03855 | 0 |
| 2017 SL16 | 1.0003294453 ± 6.52 × 10⁻⁹ | 0.2141061 ± 2.61 × 10⁻⁸ | 27.199615 ± 2.55 × 10⁻⁴ | 269.20609349 ± 9.26 × 10⁻⁵ | 283.554789 ± 1.64 × 10⁻⁴ | 24.4 | 0.01991 | 0 |
| 2017 XQ60 | 1.000328437 ± 1.08 × 10⁻⁸ | 0.1516581 ± 1.05 × 10⁻⁶ | 8.682796 ± 5.48 × 10⁻⁴ | 182.5808557 ± 1.03 × 10⁻³ | 70.4223069 ± 4.86 × 10⁻³ | 25.8 | 0.01765 | 0 |
| 2017 SL16 | 0.997175533 ± 4.93 × 10⁻⁷ | 0.0939263 ± 1.08 × 10⁻⁶ | 4.384865 ± 1.74 × 10⁻³ | 317.07727 ± 1.09 × 10⁻³ | 219.175 ± 1.32 × 10⁻³ | 27.5 | 0.01156 | 3 |
Figure 2. Short-term dynamical evolution of some parameters for the nominal orbits of 2016 CO$_{246}$, 2017 SL$_{16}$, 2017 XQ$_{60}$, and 2018 PN$_{22}$. The five basic orbital parameters ($a$, $e$, $i$, $\Omega$, $\omega$) are plotted together with the distance from Earth ($d$), the relative mean longitude ($\lambda_r$) and the Kozai parameter $\sqrt{1 - e^2 \cos i}$. 

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periodically alternate between the Apollo and Aten classes as long as it is in a HS-type orbit.

The semimajor axis short-term dynamical evolution is the typical one of an HS-type co-orbital state, being its libration period 280 yr. What is peculiar and different here is that there is a second oscillation between the minimum and maximum values of the semimajor axis. Due to the fact that the gap between the horns in its nominal HS orbit is not positioned to hold Earth in between. As 2016 CO\textsuperscript{246} moves along its orbit, the minor body passes twice through its point of minimum distance to Earth in one HS period. Moreover, this situation is seen in the graph showing the distance of the object from Earth. This corresponds to the definition of asymmetrical HS as defined in Section 2.

Furthermore, the $\lambda_6$ graph (Fig. 2a, panel c) shows that $\lambda_6$ oscillates around 180°, as expected for a minor body that is in HS co-orbital state. However and for the reasons pointed out above, when the object reaches the Earth-Sun direction in the relative orbital plane, the angle $\lambda_6$ reaches 0°. When the body moves on to the end of the horn of its HS path, $\lambda_6$ reaches about 5°. Thereafter, it returns to 0° and continues moving along its orbit.

Fig. 3 portrays that the HS dynamical behaviour is preserved in all the clone orbits. Averages of the clone parameters and the parameters of the nominal orbit are largely consistent. Asteroid 2016 CO\textsuperscript{246} will remain in an HS co-orbital state for about 900 yr. The object’s nominal orbit changes between nearly symmetric HS, QS, asymmetrical HS, and passing object within the time interval -10000 yr -10000 yr. Even in the a graph (in Fig. 3), where the largest difference between the average orbit of the clones and the nominal orbit is observed, the consistency for the time interval of -10000 yr - 10000 yr is preserved. After 2500 yr of dynamical evolution, small differences are increasing, so the average values differ from those of the nominal orbit. An interpretation of this situation leads us to conclude that the dynamical evolution is chaotic as orbits starting arbitrarily close to other diverge in a relatively short time-scale, but the overall dynamics resembles that of stable chaotic orbits (Milani & Nobili 1992). The stability of the orbit was higher in the past and the Lyapunov time was also longer in the past. If we interpret orbital stability as the object staying in a certain region as in de la Fuente Marcos & de la Fuente Marcos (2016c), all the clones of the object remain trapped in a 1:1 mean-motion resonance with Earth for 20000 yr.

The values of $\epsilon$ and $i$ oscillate periodically, alternating high $\epsilon$ and $i$. This dynamical behaviour resembles the motion of a body subjected to a Lidov-Kozai resonance (Kozai 1962; Lidov 1962; Ito & Ohtsuka 2019). However, mutual increases and decreases in both $\epsilon$ and $i$ should be proportional to each other to keep the Kozai parameter constant. Furthermore, during the same period, $\omega$ is expected to oscillate around a certain value. This oscillation can take place at different values for two different configurations. If the ratio of perturbed and perturber semimajor axes is close to zero, $\omega$ is expected to oscillate around 90° or 270° (-90°). If the asteroid is in 1:1 mean motion resonance with the perturber, the libration of $\omega$ occurs at around 0° or 180° (de la Fuente Marcos & de la Fuente Marcos 2016c).

It is seen in Fig. 3 that $\omega$ has oscillated around 90° in the time interval -10000 yr -1000 yr. Within this period, $\epsilon$ and $i$ show a proportional increase/decrease. At the same time, the nominal orbits and the clones indicate that the orbit of the object has made transitions between the QS and HS co-orbital states. Additionally, the periods in which the turning points of reciprocal decreases and increases in the $\epsilon$ and $i$ values are peaked, correspond to the periods of the QS type orbit. However, the Kozai parameter is likely to increase due to other reasons.

It is foreseen and well explained by Namouni (1999) and Christou (2000) that HS-QS transitions can be observed in classical Lidov-Kozai resonance. Besides, the backward simulation part of Fig. 3 suggesting Lidov-Kozai resonance is similar to the Fig. 4 of 2016 HO\textsubscript{3} in de la Fuente Marcos & de la Fuente Marcos (2016c), Fig. 2 of 2015 SO\textsubscript{3} in de la Fuente Marcos & de la Fuente Marcos (2016a), and Fig. 15 in Namouni (1999). It has been shown in the relevant papers that 2015 SO\textsubscript{3} is exposed to Kozai resonance, but the status of 2015 HO\textsubscript{3} fits the horseshoe-retrograde satellite orbit transitions described in Namouni (1999).

We performed additional tests for $\pm40000$ yr to see if Lidov-Kozai resonance is the cause of the effect here, and to clarify which is the main perturber. The results are shown in Fig. 4. In Fig. 4a, the integration of the orbit of the asteroid has been carried out using a model Solar system that includes the eight known planets, the dwarf planet (1) Ceres, the main-belt asteroids (2) Pallas, (4) Vesta, (10) Hygiea, (31) Euphrosyne and the Moon, as in previous integrations. Oscillations of $\omega$ around 90° in Fig. 4a correspond to transitions between the horseshoe and quasi-satellite orbit types due to the gravitational influence of other planets (probably Jupiter or Venus) as shown in Fig. 15 of Namouni (1999). However, oscillations at 0°, 180° and -180° fit the Lidov-Kozai resonance state due to the perturbation of Earth.

In Figure 4b, which corresponds to the case where Jupiter is excluded from the calculations, the number of oscillations corresponding to orbit-type transitions decreases, although they do not disappear completely. However, the number of oscillations around $\pm180$° increases. This shows that Jupiter’s perturbation cancels out the impact of the Lidov-Kozai resonance caused by Earth.

In Figure 4c, when Venus is removed from the calculations, orbit transitions appear around both $\pm90°$. Here the main perturber is Jupiter again. In Figure 4d, where all objects except Earth, the Moon, 2016 CO\textsuperscript{246} and the Sun have been removed from the calculations, Lidov-Kozai resonance is observed between -10000 yr and 40000 yr. The oscillations are around $\pm180$°.

In summary, the picture emerging from the study of the dynamical behaviour of the asteroid 2016 CO\textsuperscript{246} indicates that this object is moving along a stable chaotic orbit that shows brief episodes of Lidov-Kozai resonant behaviour.

4.2 Asteroid 2017 SL\textsubscript{16}

Asteroid 2017 SL\textsubscript{16} was discovered on 2017 September 24 by the Mt. Lemmon survey. The orbit determination of this minor body was computed on 2019 December 12 and it is based on 58 observations for a data-arc span of 739 d. Based on these observations, the condition code is currently 0. Asteroid 2017 SL\textsubscript{16} is as large as 2016 CO\textsuperscript{246} with an absolute magnitude of 25.8 mag, which suggests a diameter in the range 12–92 m for an assumed albedo in the range 0.60–0.01.
The MOID for Earth is 0.0176507 au. However, the same as 2016 CO\textsubscript{246}, it is not classified as PHA due to its absolute magnitude (25.8). It is currently in the Apollo class.

The object is moving along an asymmetrical HS-type orbit with an HS libration period of approximately 255 yr according to the $a$, and $\lambda_r$ graphs (in Fig. 2b panel a and c). As the horns of the HS in the relative orbit are approximately 20° away from the Earth-Sun direction, close approaches to Earth are more frequent and deeper (see Fig. 2b, panel b) than in the case of 2016 CO\textsubscript{246}.

In Fig. 2b, $e$ decreases with small fluctuations, while $i$ increases. At the same time, the Kozai parameter and $\omega$ show almost periodic oscillations compatible with these fluctuations. The oscillations of $\omega$ become even more significant when the orbit turns into the HS-type; thereafter, it oscillates around 70°.

The dynamical evolution of the semimajor axis $a$ in Fig. 5 shows that the nominal orbit becomes compatible with the average of its clones after it turns into HS-type. This dynamical behaviour lasts for about 2500 yr. After the first transition from HS to QS co-orbital state (about 3370 yr into the future), the average value $a$ of the clones starts to diverge from that of the nominal orbit of 2017 SL\textsubscript{16}. With the second HS-QS transition (about 4517 yr into the future), the separation between the average values of the orbital elements of the clones and the values of the nominal orbit become significant for the values of $e$, $i$ and $\omega$.

The dynamical behaviour of 2017 SL\textsubscript{16} in the interval -1000 yr - 2300 yr shows that $e$ and $i$ have consistent decreases/increases that keep the value of the Kozai parameter almost constant. However, since the moment the orbit turns into HS-type, short-period small oscillations are observed both in $\omega$ and in the value of the Kozai parameter. While $i$ and $e$ are decreasing/increasing in the 0 yr - 2300 yr interval of time, they oscillate around 70°. Approximately at 2300 yr into the future, the $i$ value reaches its maximum while the $e$ value reaches its minimum; $\omega$ begins to oscillate around 75°. Meanwhile, the Kozai parameter remains nearly constant. The peaks observed at the time corresponding to the QS transitions and the long periods of change are quite similar to those that correspond to the orbit of the minor body 2016 CO\textsubscript{246}.

Similar to the asteroid 2016 CO\textsubscript{246}, we performed additional tests for the asteroid 2017 SL\textsubscript{16} for $\pm$40000 yr range.
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4.3 Asteroid 2017 XQ₆₀

Asteroid 2017 XQ₆₀ was discovered by the Pan-STARRS survey (Kaiser 2004; Kaiser & Pan-STARRS Project Team 2004) on 2017 December 13. The orbit determination of the body was computed on 2019 December 12 and it is based on 80 observations for a data-arc span of 738 d. The condition code, which was 8 before December 2019, was upgraded to 0 after including the observations made on 19-20-21 December 2019 in the new orbit determination.

Asteroid 2017 XQ₆₀’s $a$, and $\lambda_r$ graphs (Fig. 2c) indicate an asymmetrical HS-type orbit with a libration period of approximately 410 yr. The object probably is the largest amongst our HS co-orbital candidates (Table 2) with an absolute magnitude of 24.4 mag, which suggests a diameter in the range 23-180 m for an assumed albedo in the range 0.60-0.01. The inclination of the asteroid (27°) is the highest value both among candidates and among existing HS co-orbitals. The eccentricity of the asteroid (0.214131) is almost as high as the eccentricities of unusual HSs (see Tables 1 and 2). The MOID value for Earth is 0.0193109 au. It is also in the Apollo class like 2017 SL₆, and 2016 CO₂₅₆. However, our numerical simulations point out that it’s current value of the semimajor axis is decreasing. In 2020, the semimajor axis value is going to drop below 1 au, and the dynamical class of the asteroid will change to Aten. It will return to the Apollo class after 211 yr of dynamical evolution.

The nominal orbit shows asymmetrical HS characteristics between -7000 yr and about 4250 yr, and the dynamical evolution of all clones is consistent with this behaviour with slight differences (Fig. 7). Unlike 2016 CO₂₅₆ and 2017 SL₆, no HS-QS transition is observed in the evolution of the orbit at any time between -10000 yr and 10000 yr. The object remains in the 1:1 mean-motion resonance region within this time interval for all clones. In addition, there are no significant differences between the nominal trajectory and the averages of the $e$, $i$, $\omega$ and $\Omega$ values for clone orbits in this time interval. Although $e$ and $i$ show a proportional increase/decrease between -10000 yr and 10000 yr, no significant oscillation of $\omega$ suggesting Lidov-Kozai resonance is observed in the same time interval.
4.4 Asteroid 2018 PN\textsubscript{22}

Asteroid 2018 PN\textsubscript{22} was discovered on 2018 August 13 by the Pan-STARRS survey (Kaiser 2004; Kaiser & Pan-STARRS Project Team 2004). The orbit determination of this minor body was computed on 2019 August 3 and it is based on 19 observations for a data-arc span of 29 d. However, based on these observations, the uncertainty of the calculated orbit is not so bad. The condition code is currently 3. Asteroid 2018 PN\textsubscript{22} is smaller than 2017 SL\textsubscript{16} and 2016 CO\textsubscript{246} with an absolute magnitude of 27.5 mag, which suggests a diameter in the range 5-42 m for an assumed albedo in the range 0.60-0.01. The Earth MOID of asteroid 2018 PN\textsubscript{22} is 0.0115656 au. The asteroid is in an Earth-like orbit with small $e$ and $i$ values and it fits the orbital parameter space of the dynamically cold resonant family where $0.985 \, \text{au} < a < 1.013 \, \text{au}$, $0 < e < 0.1$ and $0^\circ < i < 8.56^\circ$ defined by de la Fuente Marcos & de la Fuente Marcos (2013b).

According to the calculations made with the nominal orbit parameters (Fig. 2d), the object has recently reached the nearly symmetric HS-type orbit; it will continue moving along this type of orbit for around 175 yr. Its HS libration period is almost 125 yr. The object may remain longer trapped within the 1:1 mean-motion resonance with Earth or in its immediate neighbourhood, but it does not show a stable co-orbital behaviour, transitions out and in of the co-orbital state are occasionally observed.

In this case, Fig. 8 indicates that the averages of the orbital parameters of the clones differ considerably from those corresponding to the nominal orbit. During the first 60 yr of the simulations, both forward and backward in time, all clones follow fairly similar orbits as the nominal one. But from this point on, all orbital elements of the clones are beginning to follow chaotic paths that diverge. Despite its small $e$ and $i$ values, 2018 PN\textsubscript{22} is in an unstable region of the orbital parameter space leading to a chaotic dynamical behaviour. As stated in Hollabaugh & Everhart (1973), the smaller the libration period, the higher the chaotic nature of the orbit. Considering that 2018 PN\textsubscript{22} has the smallest libration period among our HS candidates, the fact that its dynamical evolution is more chaotic than those of our other HS candidates is not surprising. The probability distribution that reflects this diverging behaviour is given by: 27.5 per cent of them corresponding to a passing object (not trapped
In this work, near-Earth asteroids (NEAs) whose semimajor axes are between 0.983 and 1.017 au have been studied; it was determined that asteroids 2016 CO$_{246}$, 2017 SL$_{16}$, 2018 PN$_{22}$, 2017 XQ$_{60}$, 2018 XW$_{2}$, 2018 AN$_{23}$ are currently asymmetrical HS co-orbitals of Earth regarding their nominal orbital parameters. Numerical simulations were carried out for four of these objects, namely 2016 CO$_{246}$, 2017 SL$_{16}$, 2017 XQ$_{60}$, and 2018 PN$_{22}$, selected because of their low orbit uncertainties to ensure the reliability of the results obtained for their dynamical behaviour. For 2016 CO$_{246}$, 2017 SL$_{16}$, and 2017 XQ$_{60}$, the dynamical evolution of all clones is consistent with a dynamical scenario in which these bodies move along asymmetrical HS-type orbits. The orbit of 2018 PN$_{22}$ seems to be highly more chaotic than those of 2016 CO$_{246}$, 2017 SL$_{16}$, and 2017 SL$_{16}$: asteroid 2018 PN$_{22}$ will stay less than 200 yr in its current dynamical state. However, 2018 PN$_{22}$ has a relatively high probability (72.5%) of moving along an HS-type orbit.

In addition, the known HS Earth co-orbitals have been briefly reviewed using their current nominal orbital parameters. Asteroids 2015 YA and 2015 YQ$_{1}$ have been documented as asymmetrical HS librators (de la Fuente Marcos & de la Fuente Marcos 2016b). However, the current nominal orbit of 2015 YA will not encompass Lagrangian points L3, L4, and L5 for about 225 yr. After 225 yr of dynamical evolution, 2015 YA turns into an irregular HS libator for a brief period of time. The current dynamical behaviour of 2015 YA seems to indicate that this object rather tends to move along an unusual QS-type orbit than an HS-type one. Nevertheless, according to the dynamical behaviour observed for some clones, 2015 YA may still be able to move along an HS-type orbit but this possibility has a low probability regarding what the analysis of its current nominal orbit indicates. A similar situation is observed for 2015 YQ$_{1}$ that is changing its dynamical state in a relatively short time-scale. Its current nominal orbit indicates that it is in an unusual HS co-orbital state with a high value of $e$ and an irregular dynamical behaviour of its semimajor axis $a$.

Currently, the majority of known Earth co-orbitals are moving along HS-type orbits. HS orbits can be classified in three subgroups: unusual, nearly symmetric, and asymmetrical. The known HS co-orbitals including the new objects studied in this work divided into the three different categories are listed below. Unusual HSs: (3753) Cruithne, (54509) YORP (2000 PH$_{11}$), 2015 YQ$_{1}$: nearly symmetric HSs: 2002 AA$_{38}$, 2003 YN$_{107}$, (419624) 2010 SO$_{16}$, (454094) 2013 BS$_{45}$, 2015 SO$_{2}$, 2018 PN$_{22}$; and asymmetrical HSs: 2001 GO$_{3}$, 2006 JY$_{26}$, 2015 XX$_{169}$, 2016 CO$_{246}$, 2017 SL$_{16}$, 2017 XQ$_{60}$.

As in similar studies (Connors et al. 2005; de la Fuente Marcos & de la Fuente Marcos 2012, 2014a,c, 2016b), non-gravitational effects as well as the gravitational influence of dwarf planets and main-belt asteroids—except dwarf planet (1) Ceres and the main-belt asteroids (2) Pallas, (4) Vesta, (10) Hygiea, and (31) Euphrosyne—have been neglected. The non-inclusion of these effects has no significant influence on determining the short-term dynamical evolution of the asteroids studied here. However, they should be taken into account for long-term trajectory analyses and detailed orbital stability calculations.

Figure 6. $e-\omega$ and $t-\omega$ graphics corresponding to the +40000 yr dynamical evolution of 2017 SL$_{16}$.
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**DATA AVAILABILITY**

The data underlying this article will be shared on reasonable request to the corresponding author.

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Figure 8. Average of the short-term dynamical evolution of 1000 clone orbits of 2018 PN22 and the nominal orbit of 2018 PN22. The green curves show the average of the parameters for clone orbits; the blue curves show the parameters for the nominal orbit.

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