Asteroid 2013 ND\textsubscript{15}: Trojan companion to Venus, PHA to the Earth

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ABSTRACT
Venus has three known co-orbitals: (322756) 2001 CK\textsubscript{32}, 2002 VE\textsubscript{68} and 2012 XE\textsubscript{133}. The first two have absolute magnitudes $18 < H < 21$. The third one, significantly smaller at $H = 23.4$ mag, is a recent discovery that signals the probable presence of many other similar objects: small transient companions to Venus that are also potentially hazardous asteroids (PHAs). Here, we study the dynamical evolution of the recently discovered asteroid 2013 ND\textsubscript{15}. At $H = 24.1$ mag, this minor body is yet another small Venus co-orbital and PHA, currently close to the Lagrangian point $L_4$ and following the most eccentric path found so far for objects in this group. This transient Trojan will leave the 1:1 mean motion resonance within a few hundred years although it could be a recurrent librator. Due to its high eccentricity (0.6), its dynamics is different from that of the other three known Venus co-orbitals even if they all are near-Earth objects (NEOs). A Monte Carlo simulation that uses the orbital data and discovery circumstances of the four objects as proxies to estimate the current size of this population, indicates that the number of high-eccentricity, low-inclination Venus co-orbital NEOs may have been greatly underestimated by current models. Three out of four known objects were discovered with solar elongation at perigee greater than 135° even if visibility estimates show that less than 4 per cent of these objects are expected to reach perigee at such large elongations. Our calculations suggest that the number of minor bodies with sizes above 150 m currently engaged in co-orbital motion with Venus could be at least one order of magnitude larger than usually thought; the number of smaller bodies could easily be in many thousands. These figures have strong implications on the fraction of existing PHAs that can barely be detected by current surveys. Nearly 70 per cent of the objects discussed here have elongation at perigee < 90° and 65 per cent are prospective PHAs.

Key words: celestial mechanics – minor planets, asteroids: individual: 2002 VE\textsubscript{68} – minor planets, asteroids: individual: 2012 XE\textsubscript{133} – minor planets, asteroids: individual: 2013 ND\textsubscript{15} – minor planets, asteroids: individual: 322756 – planets and satellites: individual: Venus.

1 INTRODUCTION
Venus has no known satellites larger than about 0.3 km in radius (Sheppard & Trujillo 2009). As for unbound companions, multiple secular resonances make the presence of primordial (long-term stable) Venus co-orbitals very unlikely (Scholl, Marzari & Tricarico 2005). In contrast, numerical simulations consistently show that present-day temporary co-orbital companions to Venus should exist (Mikkola & Innanen 1992; Michel 1997; Christou 2000; Tabachnik & Evans 2000; Brasser & Lehto 2002). This theoretical prospect has been confirmed with the identification of (322756) 2001 CK\textsubscript{32}, a horseshoe-quasi-satellite orbiter (Brasser et al. 2004), 2002 VE\textsubscript{68}, a quasi-satellite (Mikkola et al. 2004) and 2012 XE\textsubscript{133}, a former $L_5$ Trojan moving into a horseshoe orbit (de la Fuente Marcos & de la Fuente Marcos 2013). Besides being temporarily trapped in a 1:1 mean motion resonance with Venus, all these objects are Mercury grazers, Venus crosses and Earth crossers. As Earth crossers, they are also members of the near-Earth object (NEO) population that experiences close approaches to our planet. The minimum orbit intersection distances (MOIDs) with the Earth of 322756, 2002 VE\textsubscript{68} and 2012 XE\textsubscript{133} are 0.08, 0.03 and 0.003 au, respectively. This property makes them objects of significant interest.

Potentially hazardous asteroids (PHAs) are currently defined as having an Earth MOID of 0.05 au or less and an absolute magnitude, $H$, of 22.0 or less (Marsden 1997); following this definition and at the time of this writing, there are 1451 known PHAs\textsuperscript{1} if the size limit (> 150 m, for an assumed albedo of 13 per cent) is lowered or ignored (hereafter, the PHA regime), there are several thousands of known PHAs. Lowering the size limit appears to be well supported by the analysis of the effects of the recent impact of a small asteroid in central Russia, the Chelyabinsk Event (see e.g. Brown et al. 2013), which demonstrates that even smaller objects (under 20 m) can still cause significant damage if they hit densely

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\textsuperscript{1} http://neo.jpl.nasa.gov/neo/groups.html
and uncertainties in Table 1 is the Jet Propulsion Laboratory (JPL) Small-Body Database.

Its very small relative semimajor axis, \(|a - a_{\text{Venus}}| \approx 0.0002 \pm 0.0002 \) au (the smallest found so far), makes this object a clear candidate to be a Venus co-orbital. It completes one orbit around the Sun in 224.79 d or 0.6154 yr when Venus does it in 224.70 d or 0.6152 yr. Its current orbit is based on 21 observations with a data-arc span of 26 d. As expected of recent discoveries, the quality of the orbits of both 2012 XE_{133} and 2013 ND_{15} is currently lower than that of the other two co-orbitals. It is similar, however, to the one available when the other two objects were identified as unbound companions to Venus back in 2004 (de la Fuente Marcos & de la Fuente Marcos 2013). This object has \(H = 24.1\) mag (assumed \(G = 0.15\)) or a diameter of 40 to 100 m for an assumed albedo in the range 0.20–0.04.

As a Venus co-orbital candidate, the key parameter to study is the oscillation of the difference between the mean longitudes of the object and Venus or relative mean longitude, \(\lambda\). The mean longitude of an object is given by \(M = M + \Omega + \omega\) where \(M\) is the mean anomaly, \(\Omega\) is the longitude of the ascending node and \(\omega\) is the argument of perihelion. An object is co-orbital if \(\lambda\) oscillates (librates) around a constant value; if \(\lambda\) can take any value (circulates) then we have a passing object. For additional details on co-orbital dynamical behaviour see e.g. Namouni (1999) and Christou (2000).

To confirm the co-orbital nature of 2013 ND_{15} with Venus, we have carried out \(N\)-body simulations using the Hermite integrator (Makino 1991; Aarseth 2003) in both directions of time for 10 kyr. The standard version of this direct \(N\)-body code is publicly available from the IoA web site Relativistic terms and the role of the Yarkovsky effect may have a non-negligible role on the medium- and long-term evolution of objects as small as 2013 ND_{15}. 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 2013 ND_{15}. Detailed observations obtained during future encounters with the Earth or from the Gaia mission should be able to provide that information and eventually improve the modelling presented here (see e.g. Carbognani et al. 2012; Cellino & Dell’Oro 2012; Delbò et al. 2012).

Our model Solar system includes the perturbations by the eight major planets, treating the Earth and the Moon as two separate objects, the barycentre of the dwarf planet Pluto–Charon system and the three largest asteroids. We use initial conditions (positions and velocities in the barycentre of the Solar system referred to the JD2456600.5 epoch, \(t = 0\) coincides with this epoch) provided by the JPL’s Horizons ephemeris system (Giorgini et al. 1996; Standish 1998) Relative errors in the total energy at the end of the simulations are \(< 2 \times 10^{-14}\). Additional details can be found in de la Fuente Marcos & de la Fuente Marcos (2012, 2013).

In addition to the calculations performed using the nominal orbital elements in Table 1, we have completed 100 control sim-
The motion of 2013 ND\textsubscript{15} over the time range (-200, 50) yr is displayed projected on to the ecliptic plane in a coordinate system rotating with Venus (nominal orbit in Table 1). The orbit and position of Venus are also indicated.

Our calculations (see Figs 3 and 4) left-hand panels) show that 2013 ND\textsubscript{15} has already remained in the 1:1 commensurability with Venus for a few thousand years. During this time-span, the object may have been a Trojan (L\textsubscript{4} and L\textsubscript{5}), a quasi-satellite (\(\lambda_r = 0^\circ\)) and a horseshoe libration (\(\lambda_r = 180^\circ\)). Its future orbital evolution strongly depends on the outcome of flybys with our planet during the next 250–500 yr. A very close encounter with the Earth at nearly 0.003 au may take place about 250 yr from now. Asteroid 2013 ND\textsubscript{15} may become a passing object after such an encounter but recurrent co-orbital episodes are observed for most control orbits. This is consistent with its past orbital evolution. A future better orbit may help to reduce the uncertainties in the predicted dynamical evolution but the fact is that much better orbits still translate into greater than the usual value of +60\(^\circ\). The libration centre is displaced from the typical equilateral location for eccentric orbits; the short-term evolution of the resonant angle, \(\lambda_r\), is displayed in the B-panels of Fig. 2.

All the integrated control orbits for 2013 ND\textsubscript{15} exhibit Trojan libration with respect to Venus at \(t = 0\). 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 most different from the nominal one. The orbit labelled as ‘dynamically cold’ (left-hand panels) has been obtained by subtracting thrice the uncertainty from the orbital parameters (the six elements) in Table 1. It is indeed the coldest, dynamically speaking, orbit (lowest values of \(a\), \(e\) and \(i\)) compatible with the current values of its orbital parameters. In contrast, the orbit labelled as ‘dynamically hot’ (right-hand panels) was computed by adding three times the value of the uncertainty to the orbital elements in Table 1. This makes this trajectory the hottest possible in dynamical terms (largest values of \(a\), \(e\) and \(i\)). All the control orbits exhibit consistent behaviour within a few hundred years of \(t = 0\). Asteroid 2013 ND\textsubscript{15} is indeed a Venus Trojan according to the current observational uncertainties or at a confidence level > 99 per cent. However, its Trojan dynamical status is only temporary and the tadpole orbit that it currently follows (see Fig. 1), short lived.

### Table 1. Heliocentric Keplerian orbital elements (and the 1\(\sigma\) uncertainty) of asteroids 2013 ND\textsubscript{15}, (322756) 2001 CK\textsubscript{32}, 2002 VE\textsubscript{68} and 2012 XE\textsubscript{133} (Epoch = JD2456600.5, 2013-Nov-4.0; J2000.0 ecliptic and equinox. Source: JPL Small-Body Database).

| 2013 ND\textsubscript{15} | 322756 | 2002 VE\textsubscript{68} | 2012 XE\textsubscript{133} |
|---------------------------|--------|----------------|--------------------------|
| Semimajor axis, \(a\) (au) | 0.7235±0.0002 | 0.72545780±0.000000004 | 0.7235649302±0.000000005 | 0.72297±0.00014 |
| Eccentricity, \(e\) | 0.6115±0.0006 | 0.3824353±0.00000002 | 0.41033045±0.00000005 | 0.4332±0.0003 |
| Inclination, \(i\) (°) | 4.794±0.009 | 8.13201±0.00002 | 9.005960±0.000013 | 6.711±0.006 |
| Longitude of the ascending node, \(\Omega\) (°) | 95.84±0.02 | 109.501±0.0002 | 231.579688±0.000005 | 281.095±0.006 |
| Argument of perihelion, \(\omega\) (°) | 19.69±0.02 | 234.0956±0.0002 | 355.463807±0.000014 | 337.085±0.007 |
| Mean anomaly, \(M\) (°) | 357.57±0.06 | 1.35441±0.00009 | 123.30681±0.00003 | 351.6±0.2 |
| Perihelion, \(q\) (au) | 0.2811±0.0005 | 0.44801718±0.00000011 | 0.42671696±0.00000004 | 0.4098±0.0003 |
| Aphelion, \(Q\) (au) | 1.1660±0.0002 | 1.002898585±0.00000006 | 1.0205591818±0.00000007 | 1.0361±0.0002 |
| Absolute magnitude, \(H\) (mag) | 24.1 | 18.9 | 20.5 | 23.4 |

3 CURRENT DYNAMICAL STATUS AND EVOLUTION

The motion of 2013 ND\textsubscript{15} over the time range (-200, 50) yr as seen in a coordinate system rotating with Venus projected on to the ecliptic plane is plotted in Fig. 1 (nominal orbit in Table 1). This minor body is a Venus co-orbital currently following a tadpole orbit around Venus’ Lagrangian point L\textsubscript{4}; it is, therefore, a Trojan (see e.g. Murray & Dermott 1999). Due to its significant eccentricity and in accordance to theoretical predictions (Namouni, Christou & Murray 1999; Namouni & Murray 2000), the libration angle is
Figure 2. Comparative short-term dynamical evolution of various parameters for an orbit arbitrarily close to the nominal one of 2013 ND₁₅ as in Table I (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, \( \lambda_r \) (B-panels). The orbital elements \( a - a_{\text{Venus}} \) (C-panels), \( e \) (D-panels), \( i \) (E-panels) and \( \omega \) (F-panels). The distances to the descending (thick line) and ascending nodes (dotted line) appear in the G-panels. Earth’s and Mercury’s aphelion and perihelion distances are also shown.

4 ASTEROID 2013 ND₁₅ IN CONTEXT

Fig. 4 displays the comparative evolution of the osculating orbital elements and other parameters of interest of all the known Venus co-orbitals (nominal orbits in Table I). It is clear that the higher eccentricity (mainly) and slightly lower inclination of the orbit of 2013 ND₁₅ are responsible for the obvious differences observed in the figure. One common feature is also evident, all these objects switch between resonant states relatively frequently. 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). Chaos-induced transfer from one Lagrange point to another appears to be a dynamical property common to temporarily captured Trojans of the terrestrial planets (Schwarz & Dvorak 2012).

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. The evolution over time of the location of the nodes of (322756) 2001 CK₃₂, 2002 VE₆₈ and 2012 XE₁₃₃ is very similar; they remain confined between Mercury’s and Earth’s aphelia, 0.4667 au and 1.0167 au, respectively. In sharp contrast, the nodes of 2013 ND₁₅ exhibit a wider oscillation range, 0.3–1.2 au. The lower inclination translates into more frequent flybys with the Earth. These encounters are not as deep as in the case of some of the other three objects but they occur more often. Asteroid 2013 ND₁₅ seems to be an extreme version of 2012 XE₁₃₃ and its orbit is even more unstable.

5 BUT, HOW MANY ARE OUT THERE?

The model in Morais & Morbidelli (2006) only strictly applies if \( H < 22 \) and it predicts the existence of two Venus co-orbitals with absolute magnitude brighter than 21 mag. There are two known
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Figure 3. The resonant angle, $\lambda_1$, for the nominal orbit of 2013 ND$_{15}$ in Table 1 (red line) and two of the control orbits. The blue line corresponds to a particular control orbit that was chosen close to the 3σ limit so its orbital elements are most different from the nominal ones. The third orbit (green line) has osculating elements within 1σ of those of the nominal orbit.

Table 2. Equatorial coordinates (J2000.0), apparent magnitudes (with filter), solar elongation, $e$, and phase, $\phi$, at discovery time of known Venus co-orbitals. Source: MPC Database.

| Object       | $\alpha$ (h:m:s) | $\delta$ (°:′:″) | $m$ (mag) | $\theta$ (°) | $\phi$ (°) |
|--------------|------------------|------------------|-----------|--------------|-------------|
| 2001 CK$_{32}$ | 16:54:52.51      | +33:02:23.9      | 17.2      | 83.8         | 90.0        |
| 2002 VE$_{68}$ | 01:05:00.91      | +26:34:22.8      | 14.1 (R)  | 150.9        | 28.2        |
| 2012 XF$_{133}$ | 07:32:51.54      | +59:02:11.9      | 18.5 (V)  | 137.0        | 40.5        |
| 2013 ND$_{15}$ | 21:21:58.739     | -26:52:18.69     | 20.5 (w)  | 154.3        | 22.3        |

objects within that limit: (322756) 2001 CK$_{32}$ and 2002 VE$_{68}$. Morais & Morbidelli (2006) already considered surprising that the currently known sample of these objects was apparently complete up to $H < 21$. This result is even more extraordinary when we realize that ongoing NEO search programmes are not specifically targeting this class of objects. A look back into the discovery circumstances of individual objects, as compiled in Table 2, may help us to understand better this intriguing issue. In particular, the value of the solar elongation or angle between the Sun and the object as seen from the Earth at the time of discovery can provide valuable clues on how abundant these objects really are. The source of the data in Table 2 is the Minor Planet Center (MPC) Database.

Three out of four objects were found at elongations $> 135^\circ$. Observationally speaking, this is not unusual as NEO surveys mainly focus on the regions of the sky at elongations in that range. However, and in theory, most of the objects discussed here are unlikely to routinely reach perigee at such large elongations as they spend most of the time in the unobservable (daytime) sky. Morais & Morbidelli (2006) estimated that 78 per cent of Venus co-orbitals are hidden in the unobservable sky (their region III) and just three per cent are found in the observable sky (their region I). In order to compute our own estimates, we performed a Monte Carlo simulation (Metropolis & Ulam 1949) in which we used the equations of the orbits of both the Earth and the object under the two-body approximation (e.g. Murray & Dermott 1999) to find the Earth-object MOID or perigee. Then we estimate the solar elongation at perigee (assumed to be the most likely discovery time) and study the resulting statistics. The orbit of the Earth used in this simulation was computed at Epoch JD 2456600.5 by the HORIZONS system. The random values of the orbital parameters of the objects follow the trends observed in Table 1, namely $0.720 < a < 0.727$, $0.3 < e < 0.7$ and $0 < i (\circ) < 10$, with both $\Omega$ and $\omega$ in (0, 360)$^\circ$. The results of $10^5$ test orbits are plotted in Fig. 5 (the value of the geocentric solar elongation is colour coded). Only perigees of less than 0.1 au (~91 per cent, 65 per cent are in the PHA regime) are considered. The fraction of these orbits reaching perigee with elongation $< 90^\circ$ (dawn to dusk sky) is 72.5 per cent; only 3.6 per cent of the objects reach perigee with elongations $> 135^\circ$.

Our results concerning the visibility of these objects are consistent with those in Morais & Morbidelli (2006); however, our interpretation is rather different. Assuming that the brightest objects are the easiest to spot and that, at elongations $> 135^\circ$, the discovery efficiency of NEO surveys approaches 100 per cent (but see below), the discovery of one single bright object, 2002 VE$_{68}$, at elongation 150$^\circ$ in 12 years of observations strongly suggests that at least 28 other similarly bright objects are still waiting for discovery. Besides, southern declinations under -30$^\circ$ and northern declinations above +80$^\circ$ are outside the coverage of most surveys. Nearly 30 per cent of the studied orbits have MOID under 0.05 au and declination under -30$^\circ$. These facts suggest that the number of asteroids with sizes above 150 m currently engaged in co-orbital motion with Venus is, at least, one order of magnitude larger than usually thought. The number of smaller bodies could easily be in many thousands and they may be secondary fragments, the result of tidal or rotational stresses (see e.g. Richardson, Bottke & Love 1998).

Fig. 6 shows the frequency distribution in equatorial coordinates at perigee for the set of orbits studied here. From this and Table 2, it is obvious that none of the known objects were discovered within the regions of the sky where the density of perigees of these objects is expected to be the highest (the ecliptic poles). Fig. 7 provides the distribution in equatorial coordinates of the actual perigees (colour coded). Once more it is clear that the known objects have been discovered far from the optimal locations. The smallest MOIDs are found in the region within $\alpha \in (14, 22)^h$ and $\delta \in (20, -70)^\circ$. Only 2013 ND$_{15}$ has been discovered close to that area of the sky. This statistical analysis can be used to implement better strategies to find these objects. In any case, optimized surveys require the use of space-based telescopes. The upcoming Gaia mission represents a very good opportunity to study this population and confirm/reject our current views. Gaia can observe close to the Sun (down to an angular distance of 45$^\circ$ from the Sun) and should be able to observe over 77 per cent of these objects, if they do exist. In sharp contrast, nearly 70 per cent of the objects discussed here have elongation at perigee $< 90^\circ$, and therefore, cannot be observed from the ground. The search for Trojan asteroids in the inner Solar system in general, and using Gaia in particular, has been discussed by Todd, Coward & Zadnik (2012).

At this point, it may be argued that our findings are simply a corollary of the strong, but known, observational bias against detecting Atens pointed out by e.g. Mainzer et al. (2012). If we perform another Monte Carlo calculation for objects moving in Aten-type orbits ($a < 1$ au, $Q > 0.983$ au, with $Q = a (1 + e$)
being the aphelion distance, and assuming $e < 1.0$ and $i < 60^\circ$, with both $\Omega$ and $\omega$ in the range $0$–$360^\circ$ and plot the results, we obtain Fig. 8. It is true that there is indeed a strong observational bias against detecting Atens. Its actual impact is however unknown because we do not know the real distribution of the orbital elements of objects moving in Aten-type orbits. Our diagrams (here and in the previous figures) assume that the distribution of the orbital elements is uniform but it could be the case that low-eccentricity, low-inclination orbits are less likely to occur than eccentric and inclined ones due to frequent planetary close encounters. We simply do not know; a complete sample of objects is needed to provide a better answer. However, if the orbital distribution is uniform or close to uniform as assumed here, the predictions from our simple modelling show that the actual number of Atens should be significantly higher than the current tally. Consistently, the number of objects moving in orbits similar to those of known Venus co-orbitals must be higher too but their detectability is more seriously affected than that of Atens (compare frequencies in Figs 5 and 8 for an equal number of test orbits, $10^7$).

Only 26.4 per cent of the simulated Aten-type orbits reach perigee at solar elongation $< 90^\circ$; in contrast and for hypothetical Venus co-orbitals of the type discussed here, the fraction is 65.9 per cent. The difference is large enough to warrant specific consideration, separated from the bulk of the Atens. Only 29.3 per cent of the Aten-type orbits studied here are moving in the PHA regime; for Venus co-orbitals of the type discussed here this fraction amounts to 65.1 per cent. It is obvious that the overall probability of collision with our planet is much higher for the type of Venus co-orbitals discussed in this work than for the typical Aten population. The mean impact probabilities associated with Atens and other dynamical classes have been studied previously (see e.g. Steel & Baggaley 1985; Chyba 1993; Steel 1995; Dvorak & Pilat-Lohinger 1999; Dvorak & Freistetter 2001) and it is well established that Atens have the shortest lifetimes against collision, closely followed by Apollos (a factor 2–5 longer). If the objects studied here have lifetimes against collision with our planet even shorter than those of typical Atens, this population must be able to efficiently replenish the losses via some unknown mechanism(s).

Our analysis indicates that the existence of a relatively large population of Venus co-orbitals with sizes under 150 m is very
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Figure 5. Distribution in equatorial coordinates at perigee of orbits similar to those of known Venus co-orbitals as a function of the (colour coded) geocentric solar elongation (top panel). A frequency analysis of the same data (bottom panel). Only perigees < 0.1 au are considered.

Figure 6. Frequency distribution in equatorial coordinates (right ascension, top panel, and declination, bottom panel) at perigee of orbits similar to those of known Venus co-orbitals (as in Fig. 5). The best areas to search for these objects are located towards the ecliptic poles.

Figure 7. Distribution in equatorial coordinates of the (colour coded) perigees of objects moving in orbits similar to those of known Venus co-orbitals (as in Fig. 5). The green points represent the discovery coordinates of the four objects in Table 2.

Figure 8. Similar to Fig. 5 but for objects moving in Aten-type orbits. See the text for details.

likely. This small size suggests that they could be fragments of fragments. Asteroidal decay could be induced by collisional processes (e.g. Ryan 2000) but also by the combined result of thermal fatigue (e.g. Čapek & Vokrouhlický 2010) and tidal (e.g. Tóth, Vereš & Kornos 2011) or rotational stresses (e.g. Walsh, Richardson & Michel 2008). These last three processes can efficiently produce secondary fragments. The recent study of Mainzer et al. (2014) may point in that direction. Using NEOWISE (the asteroid-hunting portion of the Wide-field Infrared Survey Explorer mission) data they have found a population of tiny NEOs characterized by increasing albedo with decreasing size. This may be the result of a selection bias against finding small, dark NEOs but it may also be the specific signature of a distinctive population among small objects that are the result of secondary fragmentation.

6 CONCLUSIONS

In this paper, we have identified yet another high-eccentricity Venus co-orbital and PHA, 2013 ND_{15}. This object is the first known Venus Trojan. Our calculations indicate that this small NEO moves in a transitional, highly chaotic trajectory; it has been a co-orbital companion to Venus for just a few thousand years and it may become a passing object within the next few hundred years. Although its future orbital evolution is not easily predictable beyond that time-scale, the object may experience recurrent co-orbital episodes with Venus. However, all the calculations consistently show that 2013 ND_{15} is currently in the Trojan dynamical state. Due to its very eccentric orbit, its dynamical evolution is markedly different from that of the three previously known Venus co-orbitals, being even less stable. On the other hand, the scarcity of detected Venus co-orbitals appears to be the result of observational bias, not physical lack of objects. Our calculations suggest that the number of minor bodies with sizes above 150 m currently engaged in co-orbital motion with Venus could be at least one order of magnitude larger than usually thought; the number of smaller bodies could easily be in many thousands. These objects are better identified using space-based telescopes because nearly 70 per cent of them have solar elongation at perigee < 90°.
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