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New transient co-orbital asteroids of Venus

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ABSTRACT

Venus has no known natural satellites but has 5 known co-orbitals. **These are objects trapped in a 1:1 mean-motion resonance with Venus.** Co-orbital configurations include retrograde satellite orbits (RS), tadpole orbits (T) around the Lagrangian equilibrium points L4 or L5, and horseshoe orbits around both L4 and L5 (H). At high eccentricity or inclination, co-orbital configurations may also involve compounds of T and RS (T-RS, T-RS-T), H and RS (H-RS) orbits, or transitions between different co-orbital modes. Here we identify asteroids in 2 RS, 1 L4-tadpole, 2 H-RS, and 2 T-RS orbits, as well as 8 additional asteroids in possible temporary co-orbital status. **Although the majority of these objects do not yet have well-characterised orbits, 2020 CL1, and 2020 SB do and are very likely to be new co-orbital asteroids. With the new candidates, Venus would have a population of 20 co-orbital asteroids, comparable to those of Mars and Earth**.

Keywords: Minor planets, asteroids: general— planets and satellites: dynamical evolution and stability — celestial mechanics

1. DISCUSSION

Co-orbital asteroids are asteroids locked in a 1:1 mean-motion resonance with a planet. The classical coorbital configurations in the Circular Restricted three-body problem (CR3BP) include tadpole (T) and horseshoe (H) orbits (Murray & Dermott 1999), and retrograde satellite (RS) orbits. At large eccentricity and inclination, coorbital configurations that involve compounds of T and RS orbits, or H and RS orbits, are also possible (Namouni et al. 1999). Contrary to the planar case of the CR3BP, transitions between these co-orbital modes can occur in three dimensions due to secular variations of the eccentricity and argument of pericenter (Namouni et al. 1999).

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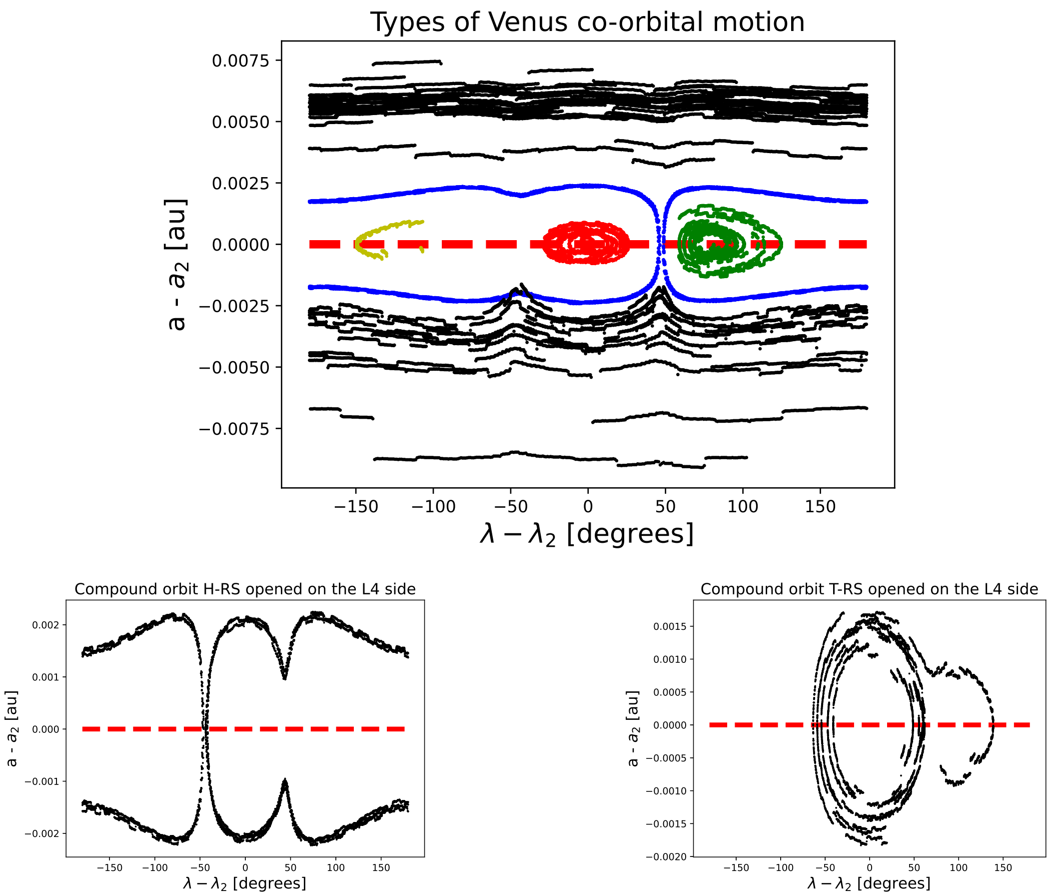

Figure 1. Top panel: projections in the $(\lambda - \lambda_2, a - a_2)$ orbital plane of an asteroid in an RS configuration (2022 BL5, red dots), of an asteroid in L4 tadpole orbit (2020 BT2, green dots), in a L5 tadpole temporary orbit (2002 XE133, yellow dots), and in a compound configuration between H and RS orbits opened on the L5 side (2024 AF6, blue dots). Black dots display the orbits of asteroids not in resonant configurations. The horizontal dashed line identifies the semi-major axis of Venus. Bottom panels: examples of an H-RS compound orbit opened on the L4 side (left panel, asteroid 322756 2001 CK32) and of the asteroid 2023 BB1 initially in a compound T-RS orbit also opened on the L4 side (right panel).

Asteroids in co-orbital configurations can be classified by visualizing the orbit in the $(\lambda - \lambda_2, a - a_2)$ plane, where $\lambda - \lambda_2$ is the resonant angle for the 1:1 mean-motion resonance with Venus (identified by the suffix 2), and a and a_2 are the asteroid and Venus osculating semi-major axes. We can distinguish between Christou (2000):

- **Retrograde Satellites (RS)**, or quasi-satellites (QS), where the orbit stays close to the perturbing planet, and oscillates around 0° in the $(\lambda - \lambda_2, a - a_2)$ plane (red dots in Figure (1)).
- **L4-tadpole orbits (TL4)**, where the orbits oscillate around the Lagrangian L4 equilibrium point, and whose shape resembles a tadpole in the Sun-planet rotating frame (green dots in Figure (1)). At high eccentricity and inclination, the center of oscillation may be displaced from 60°.
- **L5-tadpole orbits (TL5)**, which are similar to L4-tadpole orbits, but where the equilibrium point is L5 (the yellow dots in Figure(1) display the orbit of an object temporarily in such configuration).
- **Horseshoe orbits (H)**, which in the rotating frame appear as a horseshoe loop, never closing the gap at 0° with respect to the planet. There are currently no known Venus co-orbitals in such a configuration.
- **H-RS compound orbits**. These are mergers between H and RS, or betweer RS and H. An example of the former is shown blue dots in Figure(1). For this orbit, a merger from H to RS occurs on the left side of the RS orbit, or near the L5 point. The merge can also only occur on the L4 side of the orbit. The bottom-left panel of Figure(1) displays an L4 H-RS compound orbit.

- **T-RS Compound orbits**. These are mergers of T and RS An example of a compound T-RS orbit is shown in the bottom right panel of Figure(1).

- **Passing orbits (P)**, or cirulating ones (C). These are orbits for objects not in resonance and are shown as black dots in the figure top panel.

Christou (2000) showed that coorbital libration modes for co-orbitals of Earth and Venus are strong enough to survive tens of thousands of years under planetary perturbations in the Solar System. However, also because of close encounters with terrestrial planets, the present-day population of these asteroids is most likely transient (Morais & Morbidelli 2006).

Before this work, Venus had five known co-orbitals: (322756) 2001 CK32 , 524522 Zoozve (2002 VE68), 2012 XE133, 2013 ND15, and 2015 WZ12 (see de la Fuente Marcos & de la Fuente Marcos (2017) and references therein). These asteroids are in a compound H-RS orbit which opens the L4 side (322756 2001 CK32), a compound T-RS configuration opened on the L5 side (524522 Zoozve), an orbit temporarily captured in a L5-tadpole configuration (2012 XE133), an asteroid temporarily captured in a L4-tadpole orbit (2013 ND15), and an orbit in a past L4-tadpole configuration (2015 WZ12).

Since 2017, the date of the last study for Venus coorbitals, more than 17500 new NEOs have been discovered. Here, we investigated 585 NEOs in a range of ± 0.1 au from the semi-major axis of Venus (Jet Propulsion Laboratory Horizons system, accessed on July 1st, 2024). We used the Burlisch-Stoer (BS) integrator of the SWIFT package (Levison & Duncan 2013), and integrated backward and forward in time these asteroids under the influence of the eight planets, over an interval of -1000 to 1000 years. The tolerance factor for the BS integrator was 10^{-8}. All initial conditions were computed with respect to the current orbital plane of Venus. Among the new possible co-orbitals, we detected:

- **RS**: 2022 BL5 and 2022 CD remained in this resonant configuration for the whole length of the simulation. 2020 CL1 remained in an RS orbit for the range [-250, 300] yrs and was circulating before and after. The same behavior was observed for 2021 XA1, but in the longer time interval of [-1000, 850] yrs.

- **T-L4**: 2020 BT2 is the first asteroid that remained completely in a Venus L4-tadpole orbit. 2020 SV5 remained in a L4-tadpole orbit for the interval [-600, 1000] yrs.

- **T-L5** Other than the known (2012 XE133), 2020 QU5 remained in a L5-tadpole orbit between -100 and 750 yrs.

- **H-RS**: Apart from the known (322756) 2001 CK32, there are two new asteroids that spent the whole integration in compound H-RS orbits: 2020 SB, which was in a H-RS compound orbit that transitioned from a L4 to a L5 compound orbit for the whole length of the simulation, and 2024 AF6, which is in a L4 H-RS orbit. 2014 JU15, 2019 HH3, and 2021 XO3 will be in future H-RS orbits side for the ranges [200, 1000], [400, 700], and [200, 400], respectively.

- **T-RS**: Apart from the known (524522) Zoozve, 2023 BB1 was an a L5 T-RS orbit for the whole range of the simulation and 2020 SV5 remained in a L4 T-RS. 2022 UA13 was in the same type of orbit during the time interval [-50, 500] yrs, and then transitioned to circulation.

Overall, we identified 2 RS, 1 T-L4, 2 H-RS, and 2 T-RS new co-orbitals of Venus. 8 additional asteroids were in co-orbital configurations for a part of the simulated range of 2000 yrs. However, only two asteroids, 2020 CL1, and 2020 SB, have orbit conditions codes of 1, corresponding to a longitude runoff per decade of 4.4 arc seconds. The other asteroids all have codes of 5 or more, and much less reliable orbits. Their resonant status should be revised once more accurate orbital data is available.

Rather than being a dynamic oddity, Venus' co-orbitals are becoming a significant population of NEAs, like Earth' and Mars' co-orbitals. Future research should focus on extended observations, better orbit determination, detailed dynamical modeling, and physical characterization to further explore these objects.

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