

On the orbital evolution of 2020 AV₂, the first asteroid ever observed to go around the Sun inside the orbit of Venus

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ABSTRACT

The innermost section of the Solar system has not been extensively studied because minor bodies moving inside Earth’s orbit tend to spend most of their sidereal orbital periods at very low solar elongation, well away from the areas more frequently observed by programs searching for near-Earth objects. The survey carried out from the Zwicky Transient Facility (ZTF) is the first one that has been able to detect multiple asteroids well detached from the direct gravitational perturbation of the Earth–Moon system. ZTF discoveries include 2019 AQ₃ and 2019 LF₆, two Atiras with the shortest periods among known asteroids. Here, we perform an assessment of the orbital evolution of 2020 AV₂, an Atira found by ZTF with a similarly short period but following a path contained entirely within the orbit of Venus. This property makes it the first known member of the elusive Vatira population. Genuine Vatiras, those long-term dynamically stable, are thought to be subjected to the so-called von Zeipel–Lidov–Kozai oscillation that protects them against close encounters with both Mercury and Venus. However, 2020 AV₂ appears to be a former Atira that entered the Vatira orbital domain relatively recently. It displays an anticoupled oscillation of the values of eccentricity and inclination, but the value of the argument of perihelion may circulate. Simulations show that 2020 AV₂ might reach a 3:2 resonant orbit with Venus in the future, activating the von Zeipel–Lidov–Kozai mechanism, which in turn opens the possibility to the existence of a long-term stable population of Vatiras trapped in this configuration.

Key words: methods: numerical – celestial mechanics – minor planets, asteroids: general – minor planets, asteroids: individual: 2020 AV₂ – planets and satellites: individual: Mercury – planets and satellites: individual: Venus.

1 INTRODUCTION

Any minor body following an orbit contained entirely within the orbit of Earth is part of a distinctive dynamical class known as Atiras or Interior Earth Objects (IEOs) that currently has 21 known members. Such objects have aphelion distances, Q , < 0.983 au and cannot experience close flybys with the Earth–Moon system. Similarly, objects with $Q < 0.718$ au could be called Interior Venus Objects (IVOs) although there is not yet a consensus among the scientific community regarding the name of this dynamical class. Such objects can experience close flybys with neither the Earth–Moon system nor Venus, leaving Mercury as their sole direct perturber. Greenstreet, Ngo & Gladman (2012) argued that minor bodies with $0.718 \text{ au} < Q < 0.983 \text{ au}$ should be called Atiras, after the first named member of this dynamical class, and those with Q in the range $0.307\text{--}0.718 \text{ au}$ should be known as Venus Atiras or Vatiras. A systematic search for objects with $Q < 0.718 \text{ au}$ requires a well-designed space mission because they are nearly permanently con-

finned inside the Sun’s glare, but discoveries from the ground during favourable visibility windows are also possible.

The quest for finding the first object with an orbit completely interior to that of Venus started with the Near-Earth Object Surveillance Satellite (NEOSSat) mission (Hildebrand et al. 2012) that has been in operation since 2013, but it has also been attempted from the ground by the Zwicky Transient Facility (ZTF) observing system (Smith et al. 2014; Bellm & Kulkarni 2017; Ye et al. 2020) at Palomar Mountain and EURONEAR (Vaduvescu et al. 2018) from La Palma. This quest has ended recently with the discovery by ZTF of the first IVO or Vatira, 2020 AV₂ (Bacci et al. 2020). Here, we perform an assessment of the orbital evolution of 2020 AV₂ using the available data and N -body simulations. We explore the possible resonant status of this object, as well as the role of the so-called von Zeipel–Lidov–Kozai oscillation (von Zeipel 1910; Lidov 1962; Kozai 1962; Ito & Ohtsuka 2019) on its past and future dynamical evolution. This Letter is organized as follows. In Section 2, we comment on context, data, and methods. The orbital evolution of 2020 AV₂ is explored in Section 3. Our results are discussed in Section 4 and our conclusions are summarized in Section 5.

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2 CONTEXT, DATA, AND METHODS

Ngo, Greenstreet & Gladman (2011) published the first computations that led to the identification of Vatiras numerically and concluded that most objects in this class may exhibit von Zeipel–Lidov–Kozai oscillations. The von Zeipel–Lidov–Kozai mechanism requires the concurrent oscillation of the values of eccentricity, e , inclination, i , and argument of perihelion, ω , in the frame of reference of the invariable plane of the Solar system (see e.g. Murray & Dermott 1999). Most Atiras display an anticoupled oscillation of the values of e and i , but no libration of the value of ω (de la Fuente Marcos & de la Fuente Marcos 2018, 2019b,c). Therefore, no known Atiras are subjected to von Zeipel–Lidov–Kozai oscillations, but stable Vatiras may experience these oscillations (de la Fuente Marcos & de la Fuente Marcos 2019b,c).

The discovery of 2019 AQ₃ and 2019 LF₆—two Atiras with the shortest periods among known asteroids—suggested that Vatiras ought to exist and that they may be numerous because there are dynamical pathways that may turn Atiras into Vatiras and vice versa (de la Fuente Marcos & de la Fuente Marcos 2019b). Asteroid 2020 AV₂ was first observed by ZTF on 2019 January 4 (Bacci et al. 2020). Its newest orbit determination (see Table 1) is based on 135 observations for a data-arc span of 19 d. The value of its aphelion distance, $Q=0.65377\pm0.00012$ au, which is the shortest known after that of Mercury, confirms that it is an IVO or Vatira (see above). Asteroid 2020 AV₂ is relatively large with an absolute magnitude of 16.4 mag (assumed $G = 0.15$), which suggests a diameter in the range ~ 1 –8 km for an assumed albedo in the range 0.60–0.01. The value of its semimajor axis, a , is 0.55542 ± 0.00010 au, which is very similar to those of 2019 AQ₃ (0.58866153 ± 0.00000008 au) and 2019 LF₆ (0.5553 ± 0.0002 au). The orbital periods of 2019 LF₆ and 2020 AV₂ are virtually the same. De la Fuente Marcos & de la Fuente Marcos (2019c) have shown that 2019 LF₆ is not subjected to the von Zeipel–Lidov–Kozai oscillation and it is not currently in mean-motion resonance with any planet. However, it is in near-mean-motion resonance with Mercury (12:7), Venus (2:3), Earth (12:29), Mars (2:9), and Jupiter (1:29), in other words, the relevant critical angles do not librate over time about constant values (see e.g. de la Fuente Marcos & de la Fuente Marcos 2019a). Out of these near-mean-motion resonances of 2019 LF₆, the ones with Earth, Jupiter, and Mars (in this order) are the closest. For both 2019 AQ₃ and 2019 LF₆ (and several other known Atiras), the Earth–Moon system and Jupiter are the main secular perturbers (de la Fuente Marcos & de la Fuente Marcos 2019b).

Data in Table 1 as well as most input data used in our calculations have been obtained from Jet Propulsion Laboratory’s Solar System Dynamics Group Small-Body Database (JPL’s SSDG SBDB, Giorgini 2015)¹ and JPL’s HORIZONS² ephemeris system (Giorgini & Yeomans 1999). Full details of the calculations presented here are discussed in de la Fuente Marcos & de la Fuente Marcos (2012) and de la Fuente Marcos & de la Fuente Marcos (2019b).

3 ORBITAL EVOLUTION

When considering an orbit determination like the one in Table 1, the first questions that one may want to ask are how reliable is the Vatira dynamical status of 2020 AV₂ and if it has been a Vatira for

Table 1. Values of the Heliocentric Keplerian orbital elements of 2020 AV₂ and their associated 1σ uncertainties. The orbit determination is referred to epoch JD 2459000.5 (2020-May-31.0) TDB (Barycentric Dynamical Time, J2000.0 ecliptic and equinox). Source: JPL’s SBDB (solution date, 2020-Feb-01 05:47:18).

Orbital parameter	value $\pm 1\sigma$ uncertainty
Semimajor axis, a (au)	$= 0.55542\pm0.00010$
Eccentricity, e	$= 0.1771\pm0.0003$
Inclination, i (°)	$= 15.872\pm0.008$
Longitude of the ascending node, Ω (°)	$= 6.707\pm0.004$
Argument of perihelion, ω (°)	$= 187.31\pm0.02$
Mean anomaly, M (°)	$= 222.49\pm0.09$
Perihelion, q (au)	$= 0.4571\pm0.0002$
Aphelion, Q (au)	$= 0.65377\pm0.00012$
Absolute magnitude, H (mag)	$= 16.4\pm0.8$

Table 2. Cartesian state vector of 2020 AV₂: components and associated 1σ uncertainties. Epoch as in Table 1. Source: JPL’s SBDB.

Component	value $\pm 1\sigma$ uncertainty
X (au)	$= 4.468095806605945\times10^{-1}\pm5.39490272\times10^{-4}$
Y (au)	$= 4.394371500750955\times10^{-1}\pm4.11440121\times10^{-4}$
Z (au)	$= 1.071593681047472\times10^{-1}\pm1.86856646\times10^{-4}$
V_X (au/d)	$= -1.546838589354595\times10^{-2}\pm1.81479293\times10^{-5}$
V_Y (au/d)	$= 1.206070911767420\times10^{-2}\pm2.18304244\times10^{-5}$
V_Z (au/d)	$= 3.920491267033128\times10^{-3}\pm3.58100590\times10^{-6}$

a long period of time and if it will remain as such long into the future. Figure 1 shows the evolution of the values of Q and q for the nominal orbit in Table 1 in black. We observe a periodic oscillation of the values of Q and q associated with the libration of the value of e as found by de la Fuente Marcos & de la Fuente Marcos (2018, 2019b,c) for many Atiras. When integrating into the past, the value of Q increases beyond the orbit of Venus, 0.72 au; in other words, the evolution of the nominal orbit suggests that 2020 AV₂ may be a former Atira that was driven into the Vatira orbital realm as a result of multiple relatively distant encounters (i.e. beyond the Hill radius) with Mercury (Hill radius, 0.0012 au) and Venus (0.0067 au). Table 2 shows the nominal Cartesian state vector of 2020 AV₂ and associated uncertainties for the epoch used in Table 1. This information can be used to answer the questions posed above.

In addition to that of the nominal orbit determination, Fig. 1 shows the evolution of Q and q for representative control orbits with Cartesian vectors separated $\pm 3\sigma$ (in green), $\pm 6\sigma$ (in red), and $\pm 9\sigma$ (in magenta) from the nominal values in Table 2. They show that 2020 AV₂ is a statistically robust present-day Vatira and all the orbits compatible with the observations are consistent with the Vatira dynamical type, both thousands of years into the past and the future. Our calculations show that 2020 AV₂ became detached from Venus about 10^5 yr ago (Fig. 1, top panel), but also that its future orbital evolution may lead to being detached from Mercury as well, in about 2×10^5 yr (Fig. 1, bottom panel). The unusual evolution into the future of the nominal orbit will be discussed later, but it is the result of capture in the 3:2 mean-motion resonance with Venus at 0.552 au.

Ngo et al. (2011) argued that most high-inclination Vatiras exhibit von Zeipel–Lidov–Kozai oscillations and also that they may have an origin in the main asteroid belt (see their fig. 1). De la

¹ <https://ssd.jpl.nasa.gov/sbdb.cgi>

² <https://ssd.jpl.nasa.gov/?horizons>

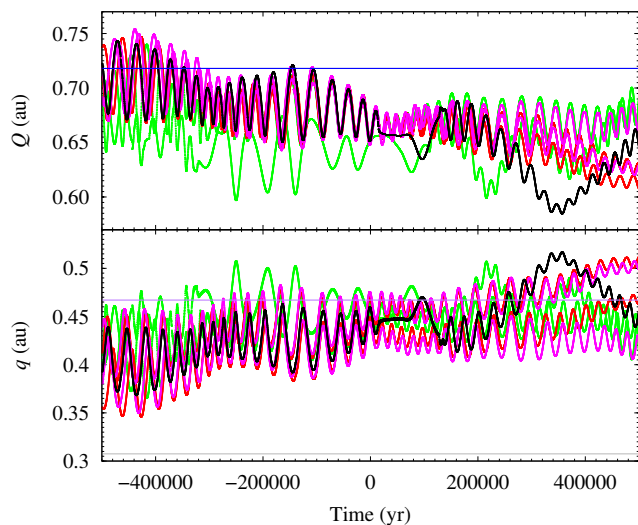


Figure 1. Evolution of the values of the aphelion (Q , top panel) and perihelion (q , bottom panel) distances of the nominal orbit (in black) of 2020 AV₂ as in Table 1 and those of control orbits with Cartesian vectors separated $\pm 3\sigma$ (in green), $\pm 6\sigma$ (in red), and $\pm 9\sigma$ (in magenta) from the nominal values in Table 2. The perihelion distance of Venus is shown in blue (top panel), the aphelion distance of Mercury is displayed in purple and its perihelion distance in grey (bottom panel). The nominal orbit evolves towards capture in the 3:2 mean-motion resonance with Venus at 0.552 au.

Fuente Marcos & de la Fuente Marcos (2019b) showed that Vatrass subjected to von Zeipel–Lidov–Kozai oscillations may be long-term stable and also that Atens may cross into the Atira orbital domain to become Vatrass at a later time. From our previous analysis, 2020 AV₂ may have come from near-Earth space and possibly from beyond. Figure 2 shows the evolution of a , e , i and ω for the nominal orbit (left-hand side set of panels), and those of control orbits with initial conditions close to -6σ (central set of panels) and -12σ values (right-hand side set of panels). Orbits often display the usual anticoupled oscillation of the values of eccentricity and inclination observed for many Atiras (de la Fuente Marcos & de la Fuente Marcos 2018, 2019b,c); however, the value of the argument of perihelion does not librate but circulates. In striking contrast, the nominal orbit and one control orbit that is most different from the nominal one show von Zeipel–Lidov–Kozai oscillations for the future evolution of 2020 AV₂. This behaviour is associated with capture in the 3:2 mean-motion resonance with Venus at 0.552 au. For the nominal orbit, capture into this resonance depends critically on close encounters with Mercury under 0.003 au in about 10 to 15 kyr from now. For more distant encounters, this capture is not observed. We have found that control orbits arbitrarily close to the nominal one do not lead to capture if close encounters with Mercury do not cross the critical value of nearly 0.003 au, which is still outside the Hill radius of the planet. Although 2020 AV₂ is probably not yet trapped in resonance with Venus, it cannot be discarded that other, not-yet-discovered Vatrass may be captured into the 3:2 mean-motion resonance with Venus, remaining there for extended periods of time. Figure 2, left-hand side set of panels, show that 2020 AV₂ may also become trapped inside the 29:1 mean-motion resonance with Jupiter at 0.5507 au in the future and perhaps experienced trapping in the 29:12 mean-motion resonance with Earth at 0.5553 au in the past. The fact is that the Vatrass orbital realm is very rich in closely spaced mean-motion resonances that may contribute

to keeping a relatively large population of minor bodies switching between the various resonant states.

4 DISCUSSION

The calculations presented in the previous section indicate that the 3:2 mean-motion resonance with Venus may play an important role in the orbital evolution of the Vatrass population. The dynamical context could be similar to that of the Hilda group asteroids that have orbital periods $2/3$ that of Jupiter. Hildas are numerous and include at least two collisional families (Brož & Vokrouhlický 2008). As with the Hildas and Jupiter, long-term stable members of the Vatrass population with $a \sim 0.552$ au may orbit the Sun reaching aphelia opposite Venus, or 60° ahead or behind Venus. In the particular case of 2020 AV₂, it might be 60° ahead (or east of) Venus. The 3:2 mean-motion resonance with Venus and its dynamical properties have been discussed within the context of ESA’s Solar Orbiter mission (Marsden & McCoy 2007).³ Gallardo (2006), top left-hand side panel of his fig. 7, has shown that the 3:2 mean-motion resonance with Venus is relatively close in strength to that of the 1:1 with Venus, which is the strongest within the Atira orbital realm.

The onset of the von Zeipel–Lidov–Kozai oscillations has been found for multiple instances on the control orbits. Figure 3 shows that even when the control orbit is not initially trapped into the 3:2 mean-motion resonance with Venus, there are viable dynamical pathways that may naturally lead to it. If the resonance can be reached relatively easily, it may be well populated although these objects have so far evaded detection because their discovery requires the observation at solar elongations below 45° . On the other hand, the von Zeipel–Lidov–Kozai oscillation may also be associated with other orbital configurations within the Vatrass orbital realm. Figure 4 shows a longer calculation for a different control orbit where von Zeipel–Lidov–Kozai oscillations are observed at about 0.85 Myr into the future when the body was not trapped into the 3:2 mean-motion resonance with Venus but had a very low value of the orbital eccentricity; in this case, the oscillation is about $\omega = 180^\circ$ so the nodal points—where the orbit crosses the ecliptic—are located at perihelion and at aphelion (Milani et al. 1989).

Ribeiro et al. (2016) argued that many Atiras remain on regular orbits for at least 1 Myr, Fig. 4 shows that this may also be the case for Vatrass. Ribeiro et al. (2016) concluded that Atiras populate a very unstable region of the inner Solar system that makes their dynamical evolution rather chaotic, Fig. 4 shows that although their orbital evolution is unstable, with multiple changes in the value of a , each transition drives the minor body towards another orbit of the Vatrass type. Although this changing evolution is consistent with chaos, the overall behaviour is significantly more quiet than that of typical near-Earth objects. As in the case of 2019 AQ₃ (de la Fuente Marcos & de la Fuente Marcos 2019b), Fig. 5 shows that the overall evolution is preserved in the post-Newtonian case.

On the other hand, a statistical analysis using the orbit model⁴ developed by the Near-Earth Object Population Observation Program (NEOPOP) and described by Granvik et al. (2018) shows that 2020 AV₂ is an outlier (in terms of size) as discussed by de la Fuente Marcos & de la Fuente Marcos (2019b) for the case of 2019 AQ₃. It is unclear why so many Atiras (and now the first

³ https://sci.esa.int/documents/34903/36699/1567259614917-MAO-WP-483_Solar-Orbiter-Mission-Analysis_i1r0_2005-11.pdf

⁴ <http://neo.ssa.esa.int/neo-population>

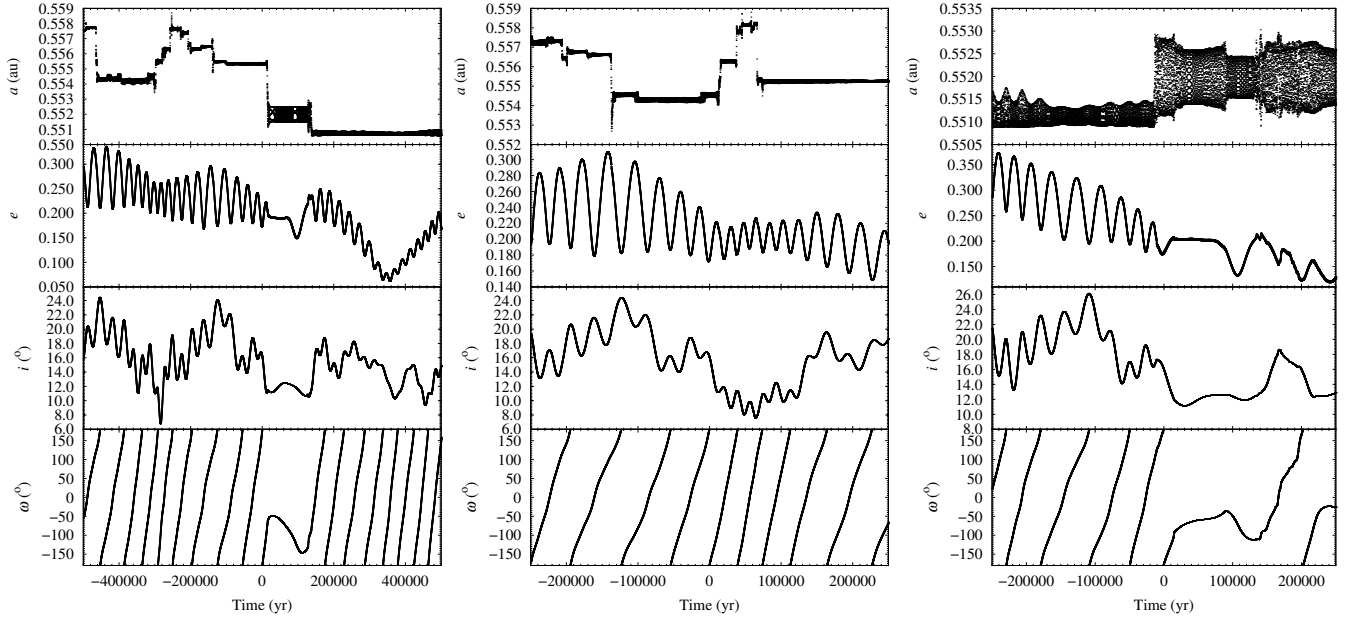


Figure 2. Evolution of the values of the semimajor axis (a , top panel), eccentricity (e , second to top panel), inclination (i , second to bottom panel), and argument of perihelion (ω , bottom panel) for the nominal orbit of 2020 AV₂ (left-hand side set of panels), one close to the -6σ orbit (central set of panels), and one close to the -12σ orbit (right-hand side set of panels). These values have been computed with respect to the invariable plane of the system.

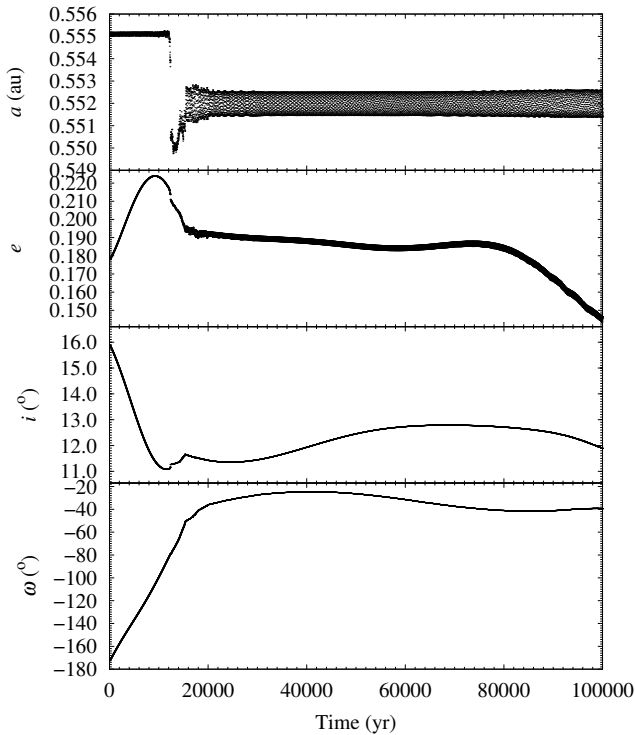


Figure 3. Similar to Fig. 2 but for a different control orbit close to the -12σ orbit.

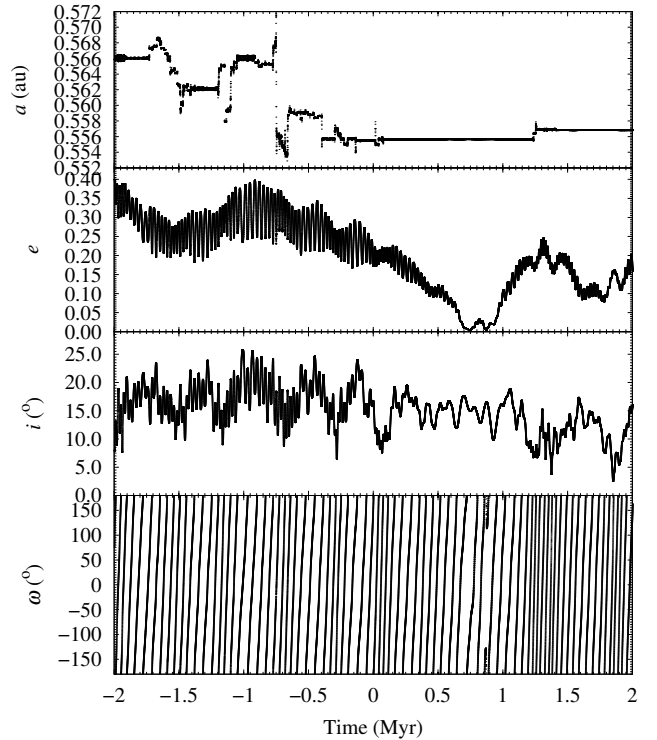


Figure 4. Similar to Fig. 2 but for a different control orbit close to the -3σ orbit and longer integration time.

5 CONCLUSIONS

Vatira) have $H < 23-25$ mag, see table 2 in [de la Fuente Marcos & de la Fuente Marcos \(2019b\)](#).

In this Letter, we have carried out an exploration of the orbital evolution of 2020 AV₂, which is the first minor body ever found follow-

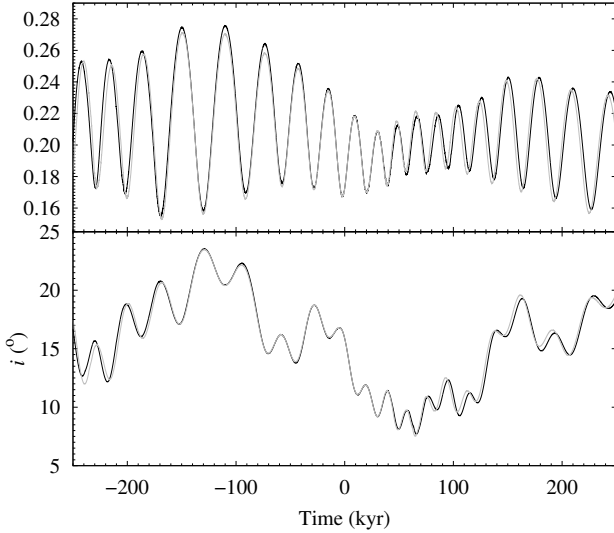


Figure 5. Evolution of the values of the eccentricity (top panel) and inclination (bottom panel) of one control orbit of 2020 AV₂ arbitrarily close to the nominal one under the Newtonian (in black) and post-Newtonian (in grey) approximations.

ing a path contained entirely within the orbit of Venus. This exploration has been performed using direct N -body simulations under the Newtonian and post-Newtonian approximations and covers the orbital domain immediately adjacent to its latest orbit determination. Although the orbit of 2020 AV₂ will certainly be improved in the future, our conclusions seem to be sufficiently robust:

- (i) All the control orbits starting within 9σ of its current nominal position and velocity show that it is a member of the Vatira group and that it was probably part of the Atira dynamical class in the relatively recent past (about 10^5 yr ago). It can experience relatively close encounters with Mercury that is its only present-day direct perturber.
- (ii) It is probably not under the influence of the von Zeipel-Lidov-Kozai mechanism, but it displays an anticoupled oscillation of the values of eccentricity and inclination in such a way that when the eccentricity reaches its maximum, the inclination reaches its minimum and vice versa.
- (iii) It is statistically possible that 2020 AV₂ could be currently subjected to the 3:2 mean-motion resonance with Venus, although it is far more probable that this Vatira is currently just outside this resonance.
- (iv) A viable dynamical pathway that can lead Vatiras into a 3:2 mean-motion resonance with Venus has been found. The capture into a resonant state is the result of multiple encounters with Mercury. When trapped in the resonance, the von Zeipel-Lidov-Kozai mechanism is active.
- (v) Vatiras may also spend significant periods of time trapped in other nearby mean-motion resonances such as the 29:1 with Jupiter at 0.5507 au or the 29:12 with Earth at 0.5553 au.
- (vi) The von Zeipel-Lidov-Kozai oscillation state can be reached via multiple dynamical pathways within Vatira orbital parameter space not necessarily linked to the 3:2 mean-motion resonance with Venus.

Our results indicate that the orbital dynamics of members of the Vatira class may be far richer than conventionally thought. Multiple transitions between Vatira paths are possible for a minor body

while still fully embedded in Vatira orbital space and this situation may continue for millions of years. Each temporarily stable path is linked to mean-motion resonances with Venus, Earth or Jupiter.

After this work was submitted to MNRAS Letters, a relevant paper was submitted by S. Greenstreet to astro-ph (astro-ph/2001.09083). She arrives to similar conclusions regarding the orbital evolution of 2020 AV₂ discussed here, but using different techniques (Greenstreet 2020).

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