On the dynamical evolution of 2002 VE$_{68}$

C. de la Fuente Marcos* and R. de la Fuente Marcos

Universidad Complutense de Madrid, Ciudad Universitaria, E-28040 Madrid, Spain

Accepted 2012 August 14. Received 2012 August 9; in original form 2012 July 25

ABSTRACT

Minor planet 2002 VE$_{68}$ was identified as a quasi-satellite of Venus shortly after its discovery. At that time its data-arc span was only 24 days, now it is 2,947 days. Here we revisit the topic of the dynamical status of this remarkable object as well as look into its dynamical past and explore its future orbital evolution which is driven by close encounters with both the Earth-Moon system and Mercury. In our calculations we use a Hermite integration scheme, the most updated ephemerides and include the perturbations by the eight major planets, the Moon and the three largest asteroids. We confirm that 2002 VE$_{68}$ currently is a quasi-satellite of Venus and it has remained as such for at least 7,000 yr after a close fly-by with the Earth. Prior to that encounter the object may have already been co-orbital with Venus or moving in a classical, non-resonant Near-Earth Object (NEO) orbit. The object drifted into the quasi-satellite phase from an L$_4$ Trojan state. We also confirm that, at aphelion, dangerously close encounters with the Earth (under 0.002 AU, well inside the Hill sphere) are possible. We find that 2002 VE$_{68}$ will remain as a quasi-satellite of Venus for about 500 yr more and its dynamical evolution is controlled not only by the Earth, with a non-negligible contribution from the Moon, but by Mercury as well. 2002 VE$_{68}$ exhibits resonant (or near resonant) behaviour with Mercury, Venus and the Earth. Our calculations indicate that an actual collision with the Earth during the next 10,000 yr is highly unlikely but encounters as close as 0.04 AU occur with a periodicity of 8 years.

Key words: celestial mechanics – planets and satellites: individual: Venus – asteroids: individual: 2002 VE$_{68}$ – Solar System: general – minor planets, asteroids

1 INTRODUCTION

Minor planet 2002 VE$_{68}$ was discovered by Brian A. Skiff working for the LONEOS Survey at Lowell Observatory on November 11, 2002 and confirmed by the Eschenberg Observatory the following night (Griesser, Skiff & Spahr 2002). With a value of the semi-major axis $a = 0.7237$ AU very close to that of Venus (0.7233 AU), this Aten asteroid is a Near-Earth Object (NEO) moving in a quite eccentric orbit, $e = 0.4104$, that makes it a Mercury grazer, Venus crosser and Earth crosser. It has been designated a Potentially Hazardous Asteroid (PHA) by the Minor Planets Center (MPC) and as such has been the target of Doppler studies at Goldstone (Ostro & Giorgini 2004; Benner et al. 2008; Gavrik & Gavrik 2008) on November 2002 and 2010. These radar observations suggest that its near-surface is extremely rough.

A preliminary rotational period of 13.5 h with a light curve amplitude $> 0.8$ mag (indicating a very elongated body) and an estimated size of 260 m were found by Pravec, Wolf & Sarounova (2010). Bessel $BVRI$ photometry (Barajas et al. 2011) has showed that 2002 VE$_{68}$’s mean colors are compatible with those of an X-type asteroid, perhaps similar to the E-type asteroid 2867 Steins (but also 1114 Lorraine, 5294 Omne, 796 Sarita, 107 Camilla or 3686 Antoku). Barajas et al. (2011) also calculated a synodic period of 13.5 h (confirming the previous preliminary value), an albedo of about 0.25 and an absolute visual magnitude of 20.59 that gives an effective diameter of about 200 m (also consistent to preliminary determinations). With an amplitude of 0.9 mag, its light curve suggests that it may be a contact binary in which two rubble piles orbit a centre of mass in contact with each other (the full details of this research are available from the CURE at LACC web site). This physical characterization is consistent with the battered surface suggested by radar data.

Numerical computations by Mikkola et al. (2004) soon revealed that 2002 VE$_{68}$ is in a 1:1 mean motion resonance with Venus; more specifically, the asteroid is a quasi-satellite of Venus. As such, 2002 VE$_{68}$ is not a real, gravitationally bound satellite but from Venus point of view, the object appears to travel around it over the course of a Venusian year although it actually orbits the Sun. Venus has no known satellites: Sheppard & Tru-
jillo (2009) completed a survey in search for satellites but no actual moons down to about 0.3 km in radius were detected. At the time of its identification as quasi-satellite of Venus, the arc length of 2002 VE₆₈ was only 24 days so that its orbit was not yet well known. The orbit has been improved significantly over the years and now it has an arc length of 2,947 days; besides, 2002 VE₆₈ has also been observed by radar (Ostro & Giorgini 2004; Benner et al. 2008).

Here we revisit the topic of the current dynamical status of this remarkable object as well as look into its dynamical past and explore its future orbital evolution which is driven by close encounters with both the Earth and Mercury. In our calculations we use the most updated ephemerides and include the perturbations by the eight major planets. In addition, we include perturbations from the Moon and the three largest asteroids, (1) Ceres, (2) Pallas and (4) Vesta.

This paper is organized as follows: in Section 2 the details of our numerical integrations are given. In Section 3, we present the results of our simulations. We discuss our results in Section 4. In Section 5 we compare our results with those obtained by Mikkola et al. (2004) and our conclusions are summarized in Section 6.

2 SIMULATIONS

In our calculations we directly integrate the full equations of motion using the Hermite scheme described by Makino (1991) and Aarseth (2003). Additional simulations were completed using the time-symmetric Hermite method described by Kokubo, Yoshinaga & Makino (1998) but it was found that, for the problem studied here, its overall performance was lower and the results largely identical. The Hermite scheme allows efficient numerical integration of the entire solar system thanks to the use of a block-step scheme (Aarseth 2003) in which suitably quantized time-steps enable following the orbits of Mercury or planetary satellites and trans-Neptunian objects simultaneously. The standard versions of these scalar N-body codes are publicly available from the IoA web site. These versions have been modified in order to study the orbital evolution of 2002 VE₆₈.

For accurate initial positions and velocities we used the Heliocentric ecliptic Keplerian elements provided by the JPL and initial positions and velocities based on the DE405 planetary orbital ephemerides (Standish 1998 referred to the barycentre of the Solar System. Orbits are calculated forward and backward in time. Our reference calculations include the perturbations by eight major planets (Mercury to Neptune) and treat the Earth and the Moon as a single object. As a zeroth order approximation, the Earth and the Moon can be replaced with a fictitious body at their barycentre but, in relative terms, the Moon is the largest satellite in the Solar System and, among satellites, it has one of the largest semi-major axes. Therefore, a better approximation is to resolve the Earth and the Moon as two separate bodies and assume that they are point mass objects and the only force acting between them is Newtonian gravitation, i.e. tidal dissipation is neglected. This will be our second physical model. In all cases we consider point (constant) mass objects orbiting in a conservative system; therefore, relativistic effects are ignored.

To ensure that the code used in this study was appropriate for the task, a significant amount of testing was performed and its numerical integrations have been validated against publicly available results obtained by other authors using other algorithms and physical models. Following Varadi, Runnegar & Ghil (2003), we also estimated the actual integration errors by computing the same orbits with the same physical model but with two different step sizes (or, more properly, blocks of them). In the predictor-corrector algorithm embedded into the Hermite scheme, the overall "step size" is controlled by an input amount called the time-step convergence parameter for total force polynomials, \( \eta \), which is a dimensionless accuracy parameter (Aarseth 2003). For values of \( \eta \) in the range \( 10^{-5} \) - \( 10^{-7} \), the results (and the integration errors) are similar but the error in the total energy is minimal for \( \eta = 1 \times 10^{-6} \). Then, relative errors in the total energy are as low as \( 5 \times 10^{-15} \) after 0.4 Myr. The relative error of the total angular momentum is several orders of magnitude smaller. In Figs. 1 and 2 the evolution of the semi-major axes, eccentricities and inclinations of the eight major planets are shown for 1 Myr centred on the epoch JD2456000.5. The output time-step for these plots is \( 10^3 \) yr and no filtering or smoothing was applied to the data. This output cadence is not expected to introduce any aliasing.

The evolution of the semi-major axes, eccentricities and inclinations of the inner planets (Mercury to Mars) from -0.5 to +0.5 Myr are plotted in Fig. 1. These results are similar to those in Laskar (1988, 1990), Quinn, Tremaine & Duncan (1991), Laskar, Joutel & Boudin (1993) or Ito & Tanikawa (2002). Major differences appear for Mercury but only prior to -250,000 yr and after 400,000 yr. The impact of these deviations on our results is expected to be negligible. The corresponding orbital evolution for the outer planets (Jupiter to Neptune) is displayed in Fig. 2. Eccentricities in de Pater & Lissauer (2010), Fig. 2.14, match our results very well.

We have carried out a more detailed comparison between our results and those from Varadi et al. (2003) and Laskar et al. (2011). These authors have performed long-term numerical simulations of the orbits of the major planets in our Solar System using a variety of models and integration algorithms. It is obvious that the precision of our present astronomical computations within the simulated time frame is comparable to that in these recent studies as seen in Fig. 3. The figure does not show any large differences between our results and those of Varadi et al. (2003) or Laskar et al. (2011). There are no unusual features that would hint at a major problem with our models or integration method. Here, the results of Varadi et al. (2003) paper have been obtained from Prof. Varadi’s web site. The data of Laskar et al. (2011) have been downloaded from the Astronomical Solutions for Earth paleoclimate web site. We interpret these positive comparisons as an explicit validation of our calculations.

3 RESULTS

The Venus quasi-satellite 2002 VE₆₈ is an unusual object that is directly perturbed by three of the inner planets, Mercury, Venus and the Earth. The object has a very significant eccentricity (0.41) and it is an obvious candidate to be in an unstable orbit. The overall stability of asteroids in co-orbital motion with Venus has been studied multiple times (e.g. Mikkola & Innanen 1992; Tabachnik & Evans 2000; Scholl, Marzari & Tricarico 2005; Morais & Morbidelli 2006). Results from these studies indicate that any hypothet-
On the dynamical evolution of 2002 VE₆₈

Figure 1. Evolution of the semi-major axes, eccentricities and inclinations of the four rocky planets (Mercury to Mars) from -0.5 to +0.5 Myr. These variations result from the gravitational perturbations on the motion of each planet from all the other planets of the Solar System.
Figure 2. Semi-major axes, eccentricities and inclinations of the four giant planets (Jupiter to Neptune).
Figure 3. Evolution of Earth’s orbital eccentricity according to Varadi et al. (2003) and Laskar et al. (2011) and a detail of our validation simulations (see Fig. 1 Earth). The time axis indicates that only data from the past are being displayed. The model displayed from Laskar et al. (2011) is Model A. Model 1 includes the eight major planets (Mercury to Neptune) and treat the Earth and the Moon as a single object. In Model 2, the Earth-Moon system is resolved as two separate bodies. Differences become noticeable after 250,000 years. This figure does not show large differences between our results and those of Varadi et al. (2003) or Laskar et al. (2011).

On the dynamical evolution of 2002 VE

3.1 2002 VE68: current dynamical status

2002 VE68 was identified as quasi-satellite of Venus by Mikkola et al. (2004). It was the first quasi-satellite observed and identified as such. The quasi-satellite dynamical state is a specific configuration of the 1:1 mean motion resonance with a host planet in which dynamical primordial population of Venitian co-orbitals could not possibly have survived until the present time and that any current population of co-orbital objects must be transient in nature. Asteroids in co-orbital motion with Venus undergo multiple captures/ejections in/from the 1:1 mean motion resonance and the average duration of one of these events (capture to ejection) is 32,000 yr (Morais & Morbidelli 2006). During these episodes they may become quasi-satellites or librate on horseshoe orbits or tadpole orbits (Scholl et al. 2005).

Here we present the results for the nominal orbit in Table 1. In addition to these calculations using the nominal orbital elements and for Model 3 (see below), we have performed 100 control simulations using sets of orbital elements derived from the nominal ones using the uncertainties in Table 1 at 3-σ. These control integrations take into account the uncertainties in observation and orbital determination. As listed in Table 1, the errors are very small and the results for the control orbits are very close to those of the nominal orbit shown in Figs. 4 and 5. Mikkola et al. (2004) already pointed out that the orbit of 2002 VE68 is quite chaotic. Chaotic orbits are not only sensitive to changes in the initial conditions but also to different dynamical models. Starting from the initial conditions described above, we integrate the orbits up to 20,000 yr in both directions of time although only the time interval (-10,000, 10,000) yr will be displayed in our figures. The output time-step (time resolution) in all the figures is 0.01 yr (3.65 days) and no filtering or smoothing has been applied to the data. Again, this output frequency is not expected to introduce any aliasing in our results. Our calculations do not include any modeling of the Yarkovsky and YORP effects (see, e.g., Bottke et al. 2006).

| Table 1. Heliocentric orbital elements of 2002 VE68 used in this research. (Epoch = JD2456200.5, 2012-Sep-30.0; J2000.0 ecliptic and equinox.) Values include the 1-σ uncertainty (Source: JPL Small-Body Database). |
|---|
| Semi-major axis, a = 0.7236659191 ±0.0000000005 AU |
| Eccentricity, e = 0.41035660 ±0.00000005 |
| Inclination, i = 9.005869 ±0.000013 ° |
| Longitude of ascending node, Ω = 231.584442 ±0.000005 ° |
| Argument of perihelion, ω = 355.463207 ±0.000014 ° |
| Mean anomaly, M = 202.88183 ±0.00003 ° |

Figure 4. The motion of 2002 VE68 for the next 150 yr projected onto the ecliptic plane. The coordinate system rotates with Venus. The orbit of Venus is also plotted and the actual position of Venus indicated. These results correspond to Model 3 (see the text for details). The quasi-satellite appears to follow a precessing kidney-shaped retrograde path when viewed from Venus. This figure is equivalent to Fig. 1 in Mikkola et al. (2004).
mean longitude of an object is given by $\lambda = M + \Omega + \omega$, $M$ is the mean anomaly, $\Omega$ is the longitude of ascending node and $\omega$ is the argument of perihelion. When the relative mean longitude librates around $0^\circ$, the object is in the quasi-satellite dynamical state, if it librates around $60^\circ$, the objects is called an $L_4$ Trojan, when it librates around $-60^\circ$ (or $300^\circ$), it is an $L_5$ Trojan, if the libration amplitude is larger than $180^\circ$, it is said that the object follows a horseshoe orbit and when the relative mean longitude circulates (does not oscillate around a certain value or oscillates freely) we say that the object is no longer in a 1:1 mean motion resonance with the planet, i.e. it becomes a passing object.

In Fig. 5 we plot the motion of 2002 VE$_{68}$ for the next 150 yr in a coordinate system that rotates with Venus. It appears to follow a precessing kidney-shaped retrograde path when viewed from Venus over the course of a Venusian year. This result is equivalent to that in Fig. 1 in Mikkola et al. (2004). In Fig. 6 we plot the mean longitude difference of 2002 VE$_{68}$ and Venus: its value currently librates around $0^\circ$, i.e. the object oscillates around the mean longitude of Venus. This figure is equivalent to Fig. 2 in Mikkola et al. (2004). In both Figs. 5 and 6 data from Model 3 are plotted (see details below). We confirm that the minor planet 2002 VE$_{68}$ is a quasi-satellite of Venus, it has remained in its present orbit for thousands of years and will continue trapped in this resonant state for another 500 years.

3.2 Model 1

Here we show the results from our Model 1 that includes the perturbations by the eight major planets on 2002 VE$_{68}$ for the nominal orbit in Table 1. The mean longitude difference of 2002 VE$_{68}$ and Venus is displayed in Fig. 7. As pointed out above, the relative mean longitude currently librates around $0^\circ$. 2002 VE$_{68}$ has remained for some time in the 1:1 mean motion resonance with Venus alternating among the various resonant states: $L_5$ Trojan, $L_4$ Trojan (tadpole orbits), horseshoe orbit, quasi-satellite or combinations of two or more of these orbits (some of them not displayed).

As expected for an object moving in a rather eccentric orbit and submitted to the direct perturbation of multiple planets, its orbit is certainly unstable. The orbital elements of 2002 VE$_{68}$ are plotted in Fig. 7. When the object enters the quasi-satellite dynamical state, the eccentricity increases, the inclination decreases and the value of the semi-major axis remains almost constant oscillating around the value of the semi-major axis of Venus. Large variations in both eccentricity and inclination are observed when the object goes from the $L_5$ Lagrangian point to $L_4$.

Transitions between the various resonant phases are triggered by close encounters with planets: the object is a Mercury grazer, Venus crosser and Earth crosser. In Fig. 8 we show that the distance of 2002 VE$_{68}$ from Venus remains larger than 0.1 AU until the object is ejected from the quasi-satellite dynamical state into the $L_5$ Lagrangian point to become a Venus Trojan about 500 yr from now. Encounters with Venus do not appear to be the cause of 2002 VE$_{68}$ entering or leaving the quasi-satellite phase. However, in the cases of both Mercury and the Earth, the distance of closest approach becomes relatively (Mercury) or dangerously close (Earth) to the value of the Hill sphere radius for the respective planet. The Hill sphere radius, $r_H$, is the limiting radius for orbits of planetary satellites in the presence of the Sun’s gravitational field and it is given by: $r_H \approx a(1-e)(m/(3M_\odot))^{1/3}$, where $a$ is the semi-major axis of the planet, $e$ is the eccentricity of its orbit, $m$ is the mass of the planet and $M_\odot$ is the mass of the Sun (Hamilton & Burns 1992). For Mercury, the Hill radius is 0.0012 AU and the closest approach is nearly 0.004 AU (although encounters as close as 0.003 AU are observed in our calculations) but for the Earth, the Hill radius is 0.0098 AU and the closest approaches are at 0.002 AU (0.0018 AU, 9.300 yr from now).

The object is injected into the quasi-satellite dynamical state after a close encounter with the Earth at about 0.007 AU, 11,000 yr ago (not shown in Fig. 8). In contrast, the closest approaches with Venus are at 0.07 AU but its Hill radius is 0.0067 AU. It is clear, that the current resonant behaviour of 2002 VE$_{68}$ with Venus is mainly controlled by the Earth but the secondary role of Mercury can not be neglected (the closest approach is just 2.5 times outside the Hill sphere of Mercury). At this point, let us remind the reader that in Model 1 we consider the Earth-Moon system as a single object and we follow its barycentre; therefore, when we consider the distance from 2002 VE$_{68}$ to the Earth we actually mean Earth’s barycentre. The average Earth-Moon separation is about 0.0025 AU; close encounters can, in principle, make 2002 VE$_{68}$ pass between the Earth and the Moon in the future; therefore, we must conclude that our
natural satellite will play a non-negligible role in the outcome of those close encounters and a better physical model is required in order to obtain more reliable results. On the other hand, the dynamical role of Venus may become more important after the object is ejected from the quasi-satellite state (about 500 yr from now) and eventually evolves into a passing object (10,000 yr from now); then, approaches close to the Hill sphere of Venus are possible (0.0075 AU, nearly 19,500 yr from now).

3.3 Model 2

Our previous calculations clearly indicate that, in the case of 2002 \textit{VE}_{68}, encounters with the Earth as close as 0.002 AU are possible. This is 0.8 times the distance between the Earth and the Moon. Almost certainly, the dynamical role of our natural satellite on the outcome of these close encounters cannot be neglected. In order to further investigate this claim, we will repeat the calculations including the perturbations by the eight major planets and the Moon on 2002 \textit{VE}_{68} for the nominal orbit in Table 1. Now, the Earth-Moon system is resolved as two separate bodies and assumed to be made of point mass objects; the only force acting between them is Newtonian gravitation, i.e. tidal dissipation is neglected.

Figure 7 confirms that 2002 \textit{VE}_{68} has been a quasi-satellite of Venus for some time although in these calculations it entered the quasi-satellite phase about 7,000 yr ago not 11,000 yr ago like in Model 1. In the time interval -7,000 to +1,000 yr from now the evolution of the mean longitude difference is quite similar to that in Fig. 2 of Mikkola et al. (2004). Now the object, after leaving the \textit{L}_5 Venus Trojan location, quickly enters the horseshoe-like phase. It does not immediately become an \textit{L}_4 Trojan like in Model 1. Consistently, Fig. 10 shows differences with respect to Fig. 7 although they exhibit similar behaviour in the time interval -7,000 to +1,000 yr from now. During the horseshoe-like phase, the semi-major axis remains oscillating (but with larger amplitude) around the value of the semi-major axis of Venus.

The inclusion of the Moon in the calculations has a significant impact on the evolution of the distances in Fig. 11. Now encounters as close as 0.0025 AU (not shown) are possible for both Mercury and the Earth so we may say that the resonant behaviour of 2002 \textit{VE}_{68} is controlled by both the Earth and Mercury. On the other hand, relatively close encounters with Venus are only observed prior to the quasi-satellite phase (multiple encounters under 0.03 AU) and after leaving the quasi-satellite dynamical state (0.013 AU).

3.4 Model 3

The JPL Small-Body Database indicates that the three largest asteroids, (1) Ceres, (2) Pallas and (4) Vesta, are minor perturbers of 2002 \textit{VE}_{68} and in our third and more realistic model we include the perturbations of eight planets, the Moon, (1) Ceres, (2) Pallas and (4) Vesta on the asteroid for the nominal orbit in Table 1. Figure 12 shows that the evolution of the mean longitude difference in the time interval -7,000 to +1,000 yr is very similar to those from Models 1 and 2 (see Figs. 6 and 9) confirming again that 2002 \textit{VE}_{68} has been a quasi-satellite of Venus for a period of time but that it will soon leave the quasi-satellite phase for the \textit{L}_5 Lagrangian point. The behavior of the mean longitude difference in that time range is consistent across models and differences only appear outside that time interval. The mean longitude of the asteroid currently librates around the value of the mean longitude of Venus with an amplitude of 40°-60° and an average period of about 150 yr.

The orbital evolution of the asteroid after leaving the quasi-satellite phase is significantly more complex than in previous models with multiple transitions between the various co-orbital resonant states. The evolution of the orbital elements in Fig. 13 is quite similar to that in Fig. 10 for Model 2. Figure 13 is consistent with Fig. 11 for Model 2 although close encounters with Venus after the end of the quasi-satellite phase tend to be more distant; however, encounters as close as 0.002 AU are observed about 18,000 yr into the future. As in the previous case, encounters with Mercury as close as 0.0025 AU are possible. In contrast, the closest encounters with the Earth are now at 0.006 AU but still well within its Hill sphere.

4 DISCUSSION

The asteroid 2002 \textit{VE}_{68} follows a rather eccentric orbit ($e \approx 0.4$). In general, minor body trajectories crossing the paths of one or more planets are rapidly destabilized by scatterings resulting from
close planetary approaches. The lifetime of the orbits of such objects can be relatively short. But this is only true if the orbital inclination is small, 2002 VE$_{68}$ moves in a relatively highly inclined orbit ($i \approx 9^\circ$). In the Solar System and for a minor body moving in an inclined orbit, 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. Figure 15 shows the evolution of the distance to the nodes of 2002 VE$_{68}$ along the studied time range. During the quasi-satellite phase the distance to the descending node of the object remains remarkably close to the value of Earth’s aphelion and the distance to the ascending node is also relatively close to Mercury’s aphelion. In this way, the gravitational perturbations from the Earth (mainly) and Mercury are most effective in keeping the asteroid at a safe distance from Venus. The object approaches the Earth in the vicinity of its descending node in November every 8th year. In fact, 2002 VE$_{68}$ orbits the Sun in a near 8:13 resonance with the Earth and, currently, its orbit appears to be stabilized by close encounters to the Earth every 8 years. 2002 VE$_{68}$ has a period of 0.6156 yr that is almost 8/13 (0.6154) so the Earth completes 8 orbits around the Sun in the same amount of time the asteroid completes 13. But this is not all, 2002 VE$_{68}$ is also moving in a near 9:23 resonance with Mercury. 2002 VE$_{68}$ exhibits resonant (or near resonant) behaviour with Mercury, Venus and the Earth.

On the other hand and after the object leaves its quasi-satellite path, it undergoes multiple transitions between resonant states (see Fig. 12). This significant complexity is the result of having high eccentricity and inclination, in this case compound orbits are possible (Namouni 1999; Namouni, Christou & Murray 1999). When moving in a 1:1 mean motion resonance, changes in the values of the semi-major axis, the eccentricity and the inclination are small compared to the variation of the argument of perihelion. Transfers between quasi-satellite, horseshoe and tadpole orbits are the result of the libration of the nodes (Wiegert, Innanen & Mikkola 1998). The argument of perihelion of 2002 VE$_{68}$ is displayed in Fig. 16. During the quasi-satellite phase, its value decreases at a rate of $\dot{\omega} = -0.0005^\circ$/yr. This secular change in the value of the argument of perihelion was predicted by Namouni (1999) on theoretical grounds and can be used to precisely track transitions between the quasi-satellite state and any other. Based on the precession of the argument of perihelion criterion and for Model 3, the object enters the quasi-satellite phase at about -14,000 yr and it leaves the phase 555 yr from now.

Regarding the energy balance relative to the host planet involved in the various resonant transitions, in Fig. 17 we show the total energy (specific orbital energy) of 2002 VE$_{68}$ relative to Venus.
The quasi-satellite dynamical state, even if not bound (the total relative energy is still \( > 0 \)), is significantly less energetic than the other resonant states (Trojan or any other). If, during the quasi-satellite phase the object suffers any significant deceleration as a result of, for example, drag or a distant interaction with another body (perhaps a pre-existing natural satellite) or ejection of one of the components in a binary asteroid, the object (or one of the components of a hypothetical binary system) may be permanently trapped in a retrograde orbit around the host planet. With no natural satellites, this scenario is unlikely to work for Venus or Mercury (unless the incoming asteroid is a binary) but it may be valid in other cases.

The relatively long-term quasi-satellite dynamical state of 2002 VE\(_{68}\) has been further confirmed using control orbits obtained from the nominal orbit by varying the orbital elements within the error range of the observed object (see Table 1). All the control orbits exhibit consistent behaviour in the time range -7,000 to +1,000 yr. The orbital behaviour on longer time-scales, even if not coincident, can also be discussed but in probabilistic terms. For example, 100% of the control orbits go from the \( L_4 \) Lagrangian point into the quasi-satellite phase but that transition takes place in the time frame 8,000-7,000 yr into the past for 70% of the control orbits with the remaining 30% experiencing the transition earlier than 8,000 yr ago. Prior to the \( L_4 \) Trojan state, 60% of control calculations were following horseshoe orbits, 20% were in the quasi-satellite state, 10% were in the \( L_5 \) Trojan state and the remaining 10% were following a classical, non-resonant passing orbit. So very likely and prior to the quasi-satellite phase, the object was already co-orbital with Venus and about 7,500 yr ago it became a quasi-satellite after a close encounter with the Earth.

Regarding its NEO status, our calculations indicate that an actual collision with the Earth during the next 10,000 yr is highly unlikely but a relatively close approach at 0.03782 AU on November 4, 2018, 12:41 UT will take place (the MPC\(^10\) quotes 0.03764 AU on November 4.90, 2018). Encounters that close to the Earth occur regularly and they have a periodicity of 8 years. In fact, 2002 VE\(_{68}\) was discovered during one of these close approaches, November 11, 2002. This periodicity is explained as a result of the near resonant behaviour with the Earth (see above). Within the next 100 yr, the closest approach will take place on November 12, 2106 at 0.02482 AU. No encounters closer than 0.023 AU will be recorded within the next 1,000 yr.

As for the apparently battered surface of 2002 VE\(_{68}\) we cannot avoid to speculate whether the relatively strong tidal forces generated during its frequent close fly-bys with the inner planets may have caused the object to evolve into an aggregate of shattered pieces. Also high velocity encounters with other minor bodies may have played a role as the object moves in a rather eccentric orbit in the inner solar system.

---

\(^{10}\) http://www.minorplanetcenter.net/iau/lists/PHACloseApp.html
5 COMPARISON WITH MIKKOLA ET AL. (2004)

Mikkola et al. (2004) identified 2002 VE₆₈ as the first *bona fide* quasi-satellite. They found that it has remained in the quasi-satellite dynamical state for about 7,000 years and it will remain in that phase for another 500 years. Then it will move into a temporary tadpole orbit around Venus L₅ Lagrangian point becoming a Trojan asteroid for about 700 years to later transfer to the L₄ Lagrangian point. In their work, they pointed out that due to its large eccentricity, 2002 VE₆₈ experiences frequent close approaches to the Earth as the asteroid descending node stays close to the Earth’s orbit. They concluded that although the Earth plays a major role in the orbital evolution of 2002 VE₆₈, all close encounters are well outside its Hill sphere. In their calculations, a version of the second-order Wisdom-Holman symplectic map is used (Wisdom & Holman 1991) with a time-step of 0.1 d. Mikkola et al. (2004) do not provide many details on their physical model: the actual number of planets (or any other objects) included in their calculations is not given, the initial conditions are not clearly stated, energy or angular momentum conservation are not discussed. However, our results are in general compatible and consistent with theirs although our close encounters with the Earth and Mercury in Models 2 and 3 are significantly closer than those reported by Mikkola et al. (2004), likely as a result of using a separate body for the Moon in our calculations. We confirm the Venus quasi-satellite nature of 2002 VE₆₈, also that it will leave its unusual dynamic status in a relatively short time-scale (about 500 yr) and it got into its current state after a close encounter with the Earth about 7,000 yr ago, although the actual time-scale for this event is less constrained in our calculations (7,000-14,000 yr ago). We agree that the Earth has a dominant role on the orbital evolution of 2002 VE₆₈ but Mercury is also a secondary player and due to the close encounters with the Earth-Moon system, the role of the Moon cannot be neglected. We also agree that the effect of the precession of the argument of perihelion on the upper nodal point of the object is the actual mechanism engaging or disengaging the quasi-satellite phase: the distance from the Sun to the upper nodal point coincides quite well with the value of Earth’s aphelion. They found that the e-folding time during the quasi-satellite phase was nearly 300 yr; our calculations give ~200 yr during the same period. It is also obvious from our calculations that a relatively strong gravitational interaction with the Earth injected the asteroid into its present orbit and eventually will be responsible for its future transition to a different co-orbital resonant state. The consistency between results from different integrators and different models shows that the results are solid and statistically robust.

6 CONCLUSIONS

2002 VE₆₈, a remarkable NEO, was discovered by B. Skiff in 2002 (Griesser et al. 2002) and subsequently identified as a quasi-satellite of Venus (Mikkola et al. 2004). This paper revisits the dynamical status of 2002 VE₆₈, numerically integrating its trajectory
using updated ephemerides and analyzing the results. We studied the orbit of 2002 VE$_{68}$ using different models and found good agreement between them on short time-scales. We can summarize the results of our investigation as follows:

a) We confirm the Venus quasi-satellite nature of 2002 VE$_{68}$ announced by Mikkola et al. (2004).

b) We confirm that 2002 VE$_{68}$ will leave its unusual dynamic status in a relatively short time-scale (about 500 yr).

c) We confirm that 2002 VE$_{68}$ got into its actual state after a close encounter with the Earth about 7,000-14,000 yr ago.

d) Close approaches are possible both at perihelion (with Mercury) and aphelion (with the Earth). Earth’s are more important.

e) The influence of the Moon on the dynamics of 2002 VE$_{68}$ is not negligible as very close encounters with the Earth are possible.

f) 2002 VE$_{68}$ exhibits resonant (or near resonant) behaviour with Mercury, Venus and the Earth.

g) There is no danger of impact with the Earth, Venus or Mercury in the near future. Relatively close encounters with our planet have a periodicity of 8 years. The next close approach to the Earth will take place on November 4, 2018 at 0.038 AU.

Currently, the Earth has five known objects regarded as quasi-satellites: 3753 Cruithne (Wiegert, Innanen & Mikkola 1997), 2003 YN$_{107}$ (Connors et al. 2004; Brasser et al. 2004), (164207) 2004 GU$_{9}$ (Connors et al. 2004; Brasser et al. 2004; Wiegert et al. 2005).

Figure 14. The distance of 2002 VE$_{68}$ from Mercury (top panel), Venus (middle panel) and the Earth (bottom panel) from Model 3. The middle panel is equivalent to Fig. 3 in Mikkola et al. (2004). The bottom panel is equivalent to Fig. 4 in Mikkola et al. (2004).

Figure 15. The distance to the descending (thick line) and ascending nodes (dotted line) of 2002 VE$_{68}$. Earth’s aphelion and perihelion and Mercury’s aphelion distances are also shown. The distance of the descending node coincides almost perfectly with Earth’s aphelion during the entire quasi-satellite phase. This figure is equivalent to Fig. 5 in Mikkola et al. (2004).

Figure 16. The argument of perihelion of 2002 VE$_{68}$. Its value decreases during the quasi-satellite phase at a rate of $\dot{\omega} = -0.00055^{\degree}$/yr.

Figure 17. Total energy (specific orbital energy) of 2002 VE$_{68}$ relative to Venus. The quasi-satellite state, even if not bound (energy > 0), is significantly less energetic than the other resonant states (Trojan or other).
Mikkola et al. 2006; Wajer 2010), 2006 FV$_{35}$ (Mikkola et al. 2006; Stacey & Connors 2009; Wajer 2010) and 2010 SO$_{16}$ (Christou & Asher 2011). 2002 AA$_{20}$ will become a quasi-satellite of the Earth in the future (Connors et al. 2002). Venus has one, 2002VE$_9$ (Connors et al. 2002). Clearly the more objects identified in the quasi-satellite phase the better our understanding on their stability will be. Recognizing a variety of objects in the quasi-satellite state under different dynamical environments can only improve our knowledge on the overall processes that lead to the transformation of passing orbits into co-orbital ones and vice-versa.

ACKNOWLEDGEMENTS

The authors would like to thank S. Aarseth for providing the codes used in this research and for comments on the manuscript. We also thank the referee for her/his prompt review. This work was partially supported by the Spanish ‘Comunidad de Madrid’ under grant CAM S2009/ESP-1496 (Dinámica Estelar y Sistemas Planetarios). We thank Dr. María José Fernández-Figueroa, Dr. Manuel Rego Fernández and the Department of Astrophysics of Universidad Complutense de Madrid for providing excellent computing facilities. Most of the calculations and part of the data analysis were completed on the ‘Servidor Central de Cálculo’ of the Universidad Complutense of Madrid and we thank the computing staff (Santiago Cano Alsúa) for their help during this stage. In preparation of this paper, we made use of the NASA Astrophysics Data System and the ASTRO-PH e-print server.

REFERENCES

Aarseth S. J., 2003, Gravitational N-Body Simulations, Cambridge University Press, Cambridge, p. 27
Barajas T., Hicks M. D., Mayes D., Rhoades H., Somers J., Garcia K., Foster J., Truong T., 2011, BAAS, 43, 224.02
Benest D., 1976, Celest. Mech., 13, 203
Benner L. A. M., Ostro S. J., Giorgini J. D., Jurgens R. F., Margot J.-L., Taylor P. A., Busch M. M., Shepard M. K., 2008, Icarus, 198, 294
Bottke W. F., Jr., Vokrouhlický D., Rubincam D. P., Nesvorný D., 2006 ARE&PS, 34, 157
Brasser R., Innanen K. A., Connors M., Veillet C., Wiegert P., Mikkola S., Chodas P. W., 2004, Icarus, 171, 102
Christou A. A., 2000, A&A, 356, L71
Christou A. A., Asher D. J., 2011, MNRAS, 414, 2965
Christou A. A., Wiegert P., 2012, Icarus, 217, 27
Connors M., Chodas P., Mikkola S., Wiegert P., Veillet C., Innanen K., 2002, Meteoritics Planet. Sci., 37, 1435
Connors M., Veillet C., Brasser R., Wiegert P., Chodas P., Mikkola S., Innanen K., 2004, Meteoritics Planet. Sci., 39, 1251
Danielsson L., Ip W.-H., 1972a, in Evolian A., ed, From Plasma to Planet, Wiley Interscience Division, New York, p. 353
Danielsson L., Ip W.-H., 1972b, Science, 176, 906
Dermott S. F., Murray C. D., 1981, Icarus, 48, 1
Gavrik Y. A., Gavrik A. L., 2008, Journal of Communications Technology and Electronics, 53, 1177
Griesser M., Skiff B. A., Spahr T. B., 2002, MPEC, 2002-V52
Hamilton D. P., Burns J. A., 1992, Icarus, 96, 43
Hénon M., 1969, A&A, 1, 223
Ito T., Tanikawa K., 2002, MNRAS, 336, 483
Jackson J., 1913, MNRAS, 74, 62
Kinoshita H., Nakai H., 2007, Celest. Mech. Dyn. Astron., 98, 181
Kokubo E., Yoshinaga K., Makino J., 1998, MNRAS, 297, 1067
Laskar J., 1988, A&A, 198, 341
Laskar J., 1990, Icarus, 88, 266
Laskar J., Joutel F., Boudin F., 1993, A&A, 270, 522
Laskar J., Fienga A., Gastineau M., Manche H., 2011, A&A, 532, A89
Lidov M. L., Vashkov’yak M. A., 1994a, Astronomy Letters, 20, 188
Lidov M. L., Vashkov’yak M. A., 1994b, Astronomy Letters, 20, 676
Makino J., 1991, ApJ, 369, 200
Mikkola S., Innanen K., 1992, AJ, 104, 1641
Mikkola S., Innanen K., 1997, in The Dynamical Behaviour of our Planetary System, ed. R. Dvorak, & J. Henrard, Kluwer, Dordrecht, p. 345
Mikkola S., Brasser R., Wiegert P., Innanen K., 2004, MNRAS, 351, L63
Mikkola S., Innanen K., Wiegert P., Connors M., Brasser R., 2006, MNRAS, 369, 15
Morais M. H. M., Morbidelli A., 2006, Icarus, 185, 29
Namouni F., 1999, Icarus, 137, 293
Namouni F., Christou A. A., Murray, C. D., 1999, Phys. Rev. Lett., 83, 2506
Ostro S. J., Giorgini J. D., 2004, in Belton M., Morgan T. H., Samarasinha N., Yeomans D. K., eds, Mitigation of Hazardous Comets and Asteroids, Cambridge University Press, Cambridge, p. 38
de Pater I., Lissauer J. J., 2010, Planetary Sciences, 2nd edition, Cambridge University Press, Cambridge, p. 36
Pravec P., Wolf M., Saronnova L., 2010, The Minor Planet Bulletin, 37, 171
Quinn T. R., Tremaine S., Duncan M., 1991, AJ, 101, 2287
Scholl H., Marzari F., Tricarico P., 2005, AJ, 130, 2912
Sheppard S. S., Trujillo C. A., 2009, Icarus, 202, 12
Stacey R. G., Connors M., 2009, P&SS, 57, 822
Standish E. M. 1998, JPL Planetary and Lunar Ephemerides, DE405/LE405, Interoffice Memo. 312.F-98-048, Jet Propulsion Laboratory, Pasadena, California
Szabhehely V. G., 1967, Theory of Orbits. The Restricted Problem of Three Bodies, Academic Press, New York
Tabachnik S. A., Evans N. W., 2000, MNRAS, 319, 63
Varadi F., Runnegar B., Ghil M., 2003, ApJ, 592, 620
Wajer P., 2010, Icarus, 209, 488
Wajer P., Królikowska M., 2012, Acta Astronomica, 62, 113
Wiegert P., Innanen K. A., Mikkola S., 1997, Nat., 387, 685
Wiegert P. A., Innanen K. A., Mikkola S., 1998, AJ, 115, 2604
Wiegert P., Connors M., Brasser R., Mikkola S., Stacey G., Innanen K., 2005, JRASC, 99, 145
Wisdom J., Holman M., 1991, AJ, 102, 1528