

On the dynamical evolution of 2002 VE₆₈

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ABSTRACT

The minor planet 2002 VE₆₈ was identified as a quasi-satellite of Venus shortly after its discovery. At that time its data-arc span was only 24 d; now it is 2947 d. 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 VE₆₈ currently is a quasi-satellite of Venus, and it has remained as such for at least 7000 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 VE₆₈ 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 VE₆₈ 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 yr.

Key words: celestial mechanics – minor planets, asteroids: general – planets and satellites: individual: Venus.

1 INTRODUCTION

The minor planet 2002 VE₆₈ was discovered by Brian A. Skiff working for the Lowell Observatory Near-Earth Objects Survey (LONEOS) on 2002 November 11 and confirmed by the Eschenberg Observatory the following night (Griesser, Skiff & Spahr 2002).¹ With a value of the semimajor 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 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) in 2002 and 2010 November. 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).²

Bessel *BVRI* photometry (Barajas et al. 2011)³ has showed that 2002 VE₆₈'s mean colours are compatible with those of an X-type asteroid, perhaps similar to the E-type asteroid 2867 Steins (but also 1114 Lorraine, 5294 Onnetoh, 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 with 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 website⁴). This physical characterization is consistent with the battered surface suggested by radar data.

Numerical computations by Mikkola et al. (2004) soon revealed that 2002 VE₆₈ is moving in a 1:1 mean motion resonance with Venus; more specifically, the asteroid is a quasi-satellite of Venus. As such, 2002 VE₆₈ is not a real, gravitationally bound satellite, but from the Venus point of view, the object appears to travel around

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¹ <http://www.minorplanetcenter.org/mpec/k02/k02V52.html>

² <http://www.asu.cas.cz/ppravec/neo.htm>

³ <http://www.astronomerstelegram.org/?read=3073>

⁴ http://www.lacitycollege.edu/academic/departments/physics/cure/reports/BarajasT_Sp2011_Report.pdf

it over the course of a Venusian year although it actually orbits the Sun. Venus has no known satellites: Sheppard & Trujillo (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 a quasi-satellite of Venus, 2002 VE₆₈ had an arc length of only 24 d so its orbit was not yet well known. The orbit has been improved significantly over the years and now it has an arc length of 2947 d; 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 were 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 website.⁵ 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 JPL⁶ and initial positions and velocities based on the DE405 planetary orbital ephemerides (Standish 1998)⁷ 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 semimajor 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, η , which is a dimensionless accuracy parameter (Aarseth 2003). For values of η 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 5×10^{-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 semimajor axes, eccentricities and inclinations of the eight major planets is shown for 1 Myr centred on the epoch JD245 6000.5. 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 semimajor axes, eccentricities and inclinations of the inner planets (Mercury to Mars) from -0.5 to $+0.5$ Myr is 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 the Varadi et al. (2003) paper have been obtained from Professor Varadi’s website.⁸ The data of Laskar et al. (2011) have been downloaded from the Astronomical Solutions for Earth paleoclimates website.⁹ 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

⁵ <http://www.ast.cam.ac.uk/~sverre/web/pages/nbody.htm>

⁶ <http://ssd.jpl.nasa.gov/sbdb.cgi>

⁷ http://ssd.jpl.nasa.gov/?planet_pos

⁸ <http://www.astrobiology.ucla.edu/OTHER/SSO/>

⁹ <http://www.imcce.fr/Equipes/ASD/insola/earth/La2010/index.html>

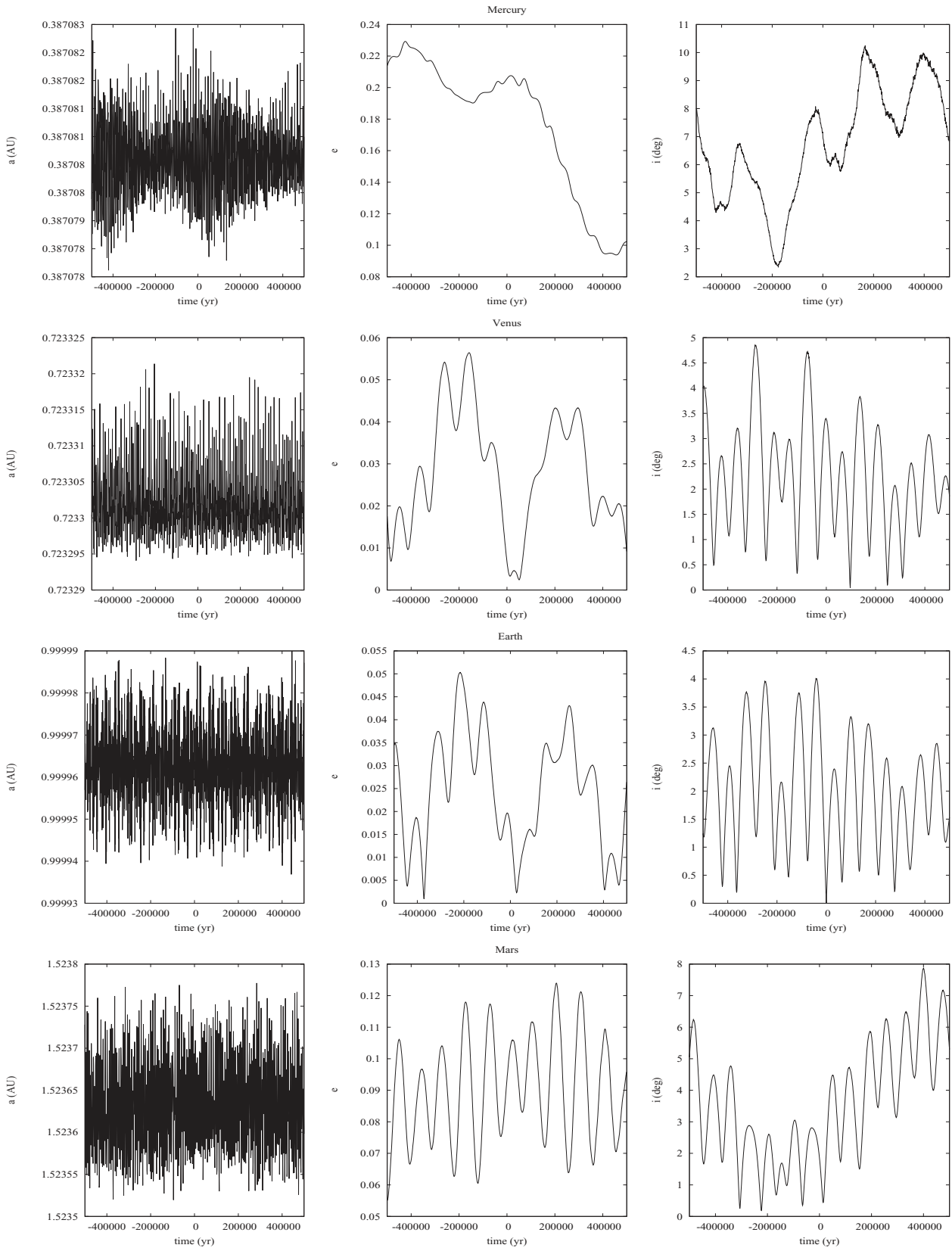


Figure 1. Evolution of the semimajor axes, eccentricities and inclinations of the four rocky planets (Mercury to Mars) from -0.5 to $+0.5$ Myr. These variations result from the gravitational perturbations on the motion of each planet from all the other planets of the Solar system.

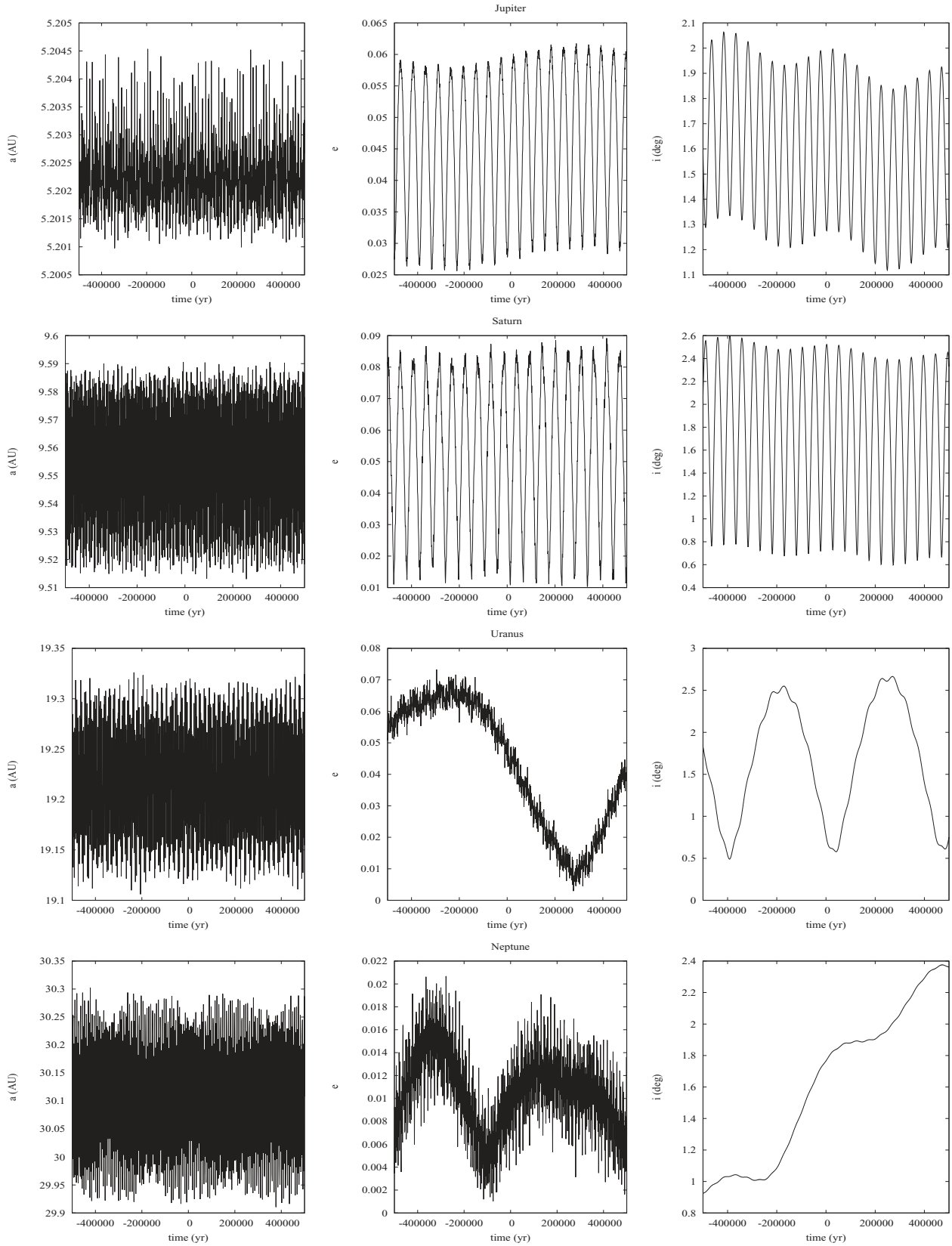


Figure 2. Semimajor axes, eccentricities and inclinations of the four giant planets (Jupiter to Neptune).

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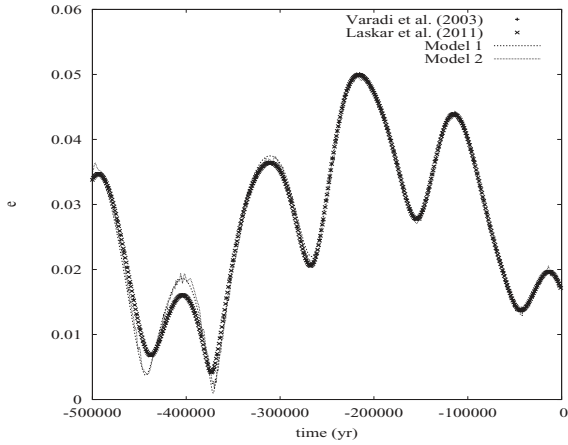


Figure 3. Evolution of the Earth’s orbital eccentricity according to Varadi et al. (2003) and Laskar et al. (2011) and a detail of our validation simulations (see Fig. 1, Earth). The time axis indicates that only data from the past are being displayed. The model displayed from Laskar et al. (2011) is 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 yr. This figure does not show large differences between our results and those of Varadi et al. (2003) or Laskar et al. (2011).

Table 1. Heliocentric orbital elements of 2002 VE₆₈ used in this research. (Epoch = JD245 6200.5, 2012-Sep-30.0; J2000.0 ecliptic and equinox.) Values include the 1σ uncertainty (Source: JPL Small-Body Database).

Semimajor axis, a	$0.723\,665\,9191 \pm 0.000\,000\,0005$ au
Eccentricity, e	$0.410\,356\,60 \pm 0.000\,000\,05$
Inclination, i	$9^{\circ}005\,869 \pm 0^{\circ}000\,013$
Longitude of ascending node, Ω	$231^{\circ}584\,442 \pm 0^{\circ}000\,005$
Argument of perihelion, ω	$355^{\circ}463\,207 \pm 0^{\circ}000\,014$
Mean anomaly, M	$202^{\circ}881\,83 \pm 0^{\circ}000\,03$

2006). Results from these studies indicate that any hypothetical primordial population of Venusian 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 3σ . 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 d) and no filtering or smoothing has been applied to the data. Again, this output frequency is not

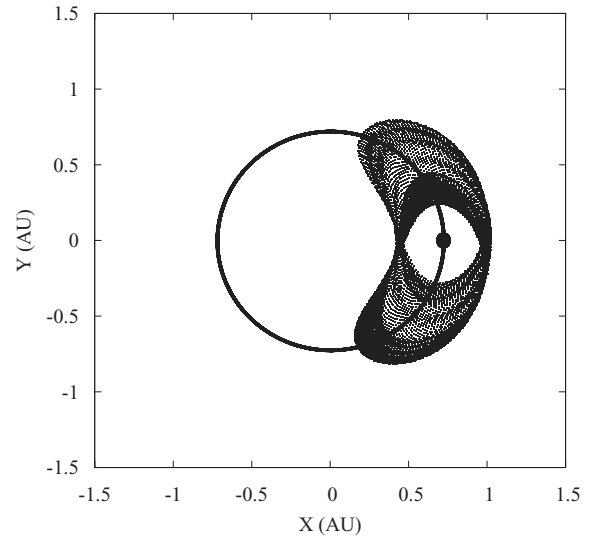


Figure 4. The motion of 2002 VE₆₈ for the next 150 yr projected on to the ecliptic plane. The coordinate system rotates with Venus. The orbit of Venus is also plotted and the actual position of Venus indicated. These results correspond to Model 3 (see the text for details). The quasi-satellite appears to follow a precessing kidney-shaped retrograde path when viewed from Venus. This figure is equivalent to fig. 1 of Mikkola et al. (2004).

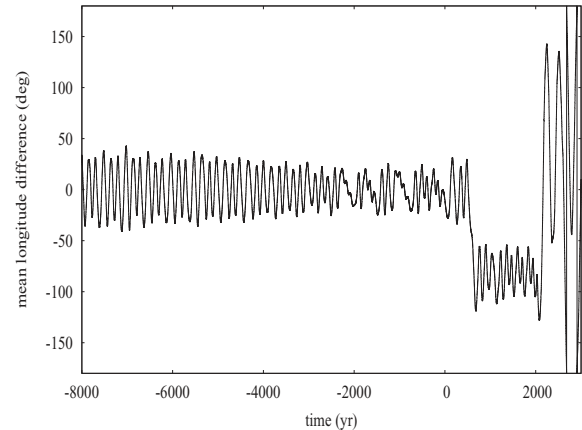


Figure 5. The mean longitude difference of 2002 VE₆₈ and Venus. It currently librates around 0° , that is characteristic of an object in the quasi-satellite dynamical state. These results correspond to Model 3 (see the text for details). This figure is equivalent to fig. 2 of Mikkola et al. (2004).

expected to introduce any aliasing in our results. Our calculations do not include any modelling of the Yarkovsky and Yarkovsky–O’Keefe–Radzievskii–Paddack (YORP) effects (see, e.g., Bottke et al. 2006).

3.1 2002 VE₆₈: current dynamical status

2002 VE₆₈ was identified as a 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 the object appears to travel around the planet but is not gravitationally bound to it: the body librates around the longitude of its associated planet but its trajectory is not closed. The term ‘quasi-satellite’ was first used in a scientific paper by Danielsson & Ip (1972a) in the context of explaining the resonant behaviour of the NEO 1685

Toro with the Earth (Danielsson & Ip 1972b). However, this early mention was not directly connected with the topic of co-orbital bodies and it is usually considered that the term was first introduced and popularized among the scientific community by Mikkola & Innanen (1997), although the concept behind it was initially studied by Jackson (1913) and the energy balance associated with the resonant state was first analysed by Hénon (1969). Further analysis was carried out by Szebehely (1967), Benest (1976), Dermott & Murray (1981) and Lidov & Vashkov'yak (1994a,b). Most of this early work was completed in the context of the restricted elliptic three-body problem.

For an asteroid following a quasi-satellite orbit, the key parameter to study is the difference between the mean longitudes of the asteroid and its host planet or relative mean longitude. The mean longitude of an object is given by $\lambda = M + \Omega + \omega$, where M is the mean anomaly, Ω is the longitude of ascending node and ω is the argument of perihelion. When the relative mean longitude librates around 0° , the object is in the quasi-satellite dynamical state, if it librates around 60° , the object is called an L_4 Trojan, when it librates around -60° (or 300°), it is an L_5 Trojan, if the libration amplitude is larger than 180° , 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. 4, we plot the motion of 2002 VE₆₈ 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 of Mikkola et al. (2004). In Fig. 5, we plot the mean longitude difference of 2002 VE₆₈ and Venus: its value currently librates around 0° , i.e. the object oscillates around the mean longitude of Venus. This figure is equivalent to fig. 2 of Mikkola et al. (2004). In both Figs 4 and 5, data from Model 3 are plotted (see the details below). We confirm that the minor planet 2002 VE₆₈ is a quasi-satellite of Venus, it has remained in its present orbit for thousands of years and it will continue to be trapped in this resonant state for another 500 yr.

3.2 Model 1

Here we show the results from our Model 1 that includes the perturbations by the eight major planets on 2002 VE₆₈ for the nominal orbit in Table 1. The mean longitude difference of 2002 VE₆₈ and Venus is displayed in Fig. 6. As pointed out above, the relative mean longitude currently librates around 0° . 2002 VE₆₈ 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 VE₆₈ 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 semimajor axis remains almost constant oscillating around the value of the semimajor 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

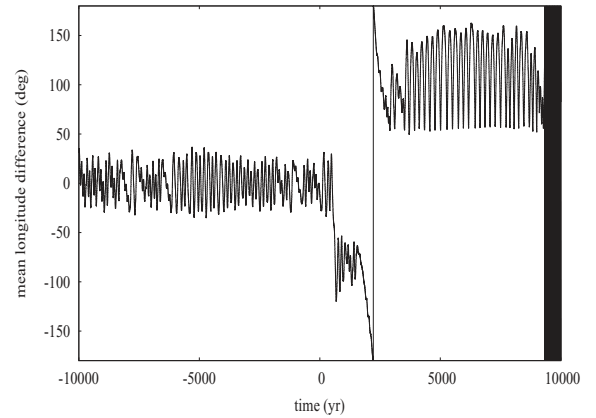


Figure 6. The mean longitude difference of 2002 VE₆₈ and Venus in the time interval $(-10\,000, 10\,000)$ yr from Model 1. The mean longitude difference currently librates around 0° . It will leave the quasi-satellite dynamical state in 500 yr from now.

2002 VE₆₈ 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 VE₆₈ entering or leaving the quasi-satellite phase. However, in the cases of both Mercury and the Earth, the distance of the 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 semimajor 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, 9300 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 VE₆₈ with Venus is mainly controlled by the Earth, but the secondary role of Mercury cannot 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 VE₆₈ to the Earth we actually mean the Earth's barycentre. The average Earth–Moon separation is about 0.0025 au; close encounters can, in principle, make 2002 VE₆₈ 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).

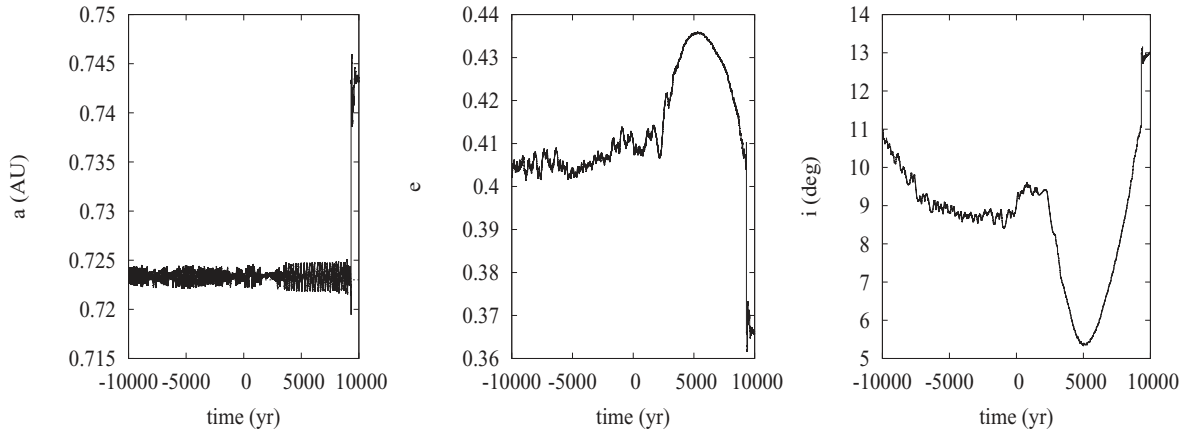


Figure 7. Orbital elements of 2002 VE₆₈ from Model 1. The value of the semimajor axis of Venus is also plotted (left-hand panel). When the object is in the quasi-satellite dynamical state, the eccentricity increases (central panel), the inclination decreases (right-hand panel) and the value of the semimajor axis remains almost constant (left-hand panel), oscillating around the value of the semimajor axis of Venus.

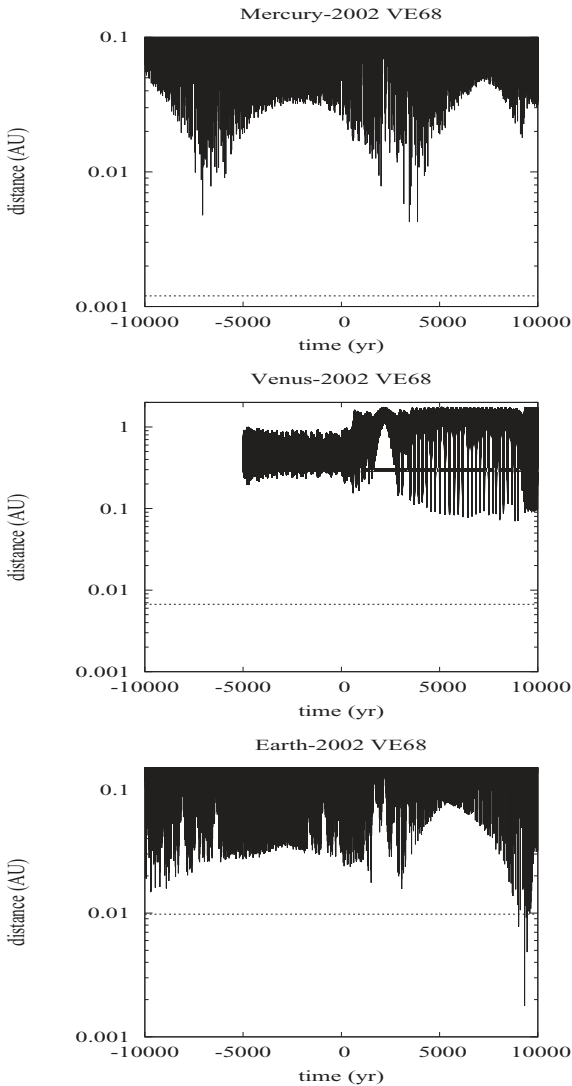


Figure 8. The distance of 2002 VE₆₈ from Mercury (top panel), Venus (middle panel) and the Earth (bottom panel) from Model 1. The value of the Hill sphere radius (see the text) for each planet is also displayed. The middle panel is equivalent to fig. 3 of Mikkola et al. (2004). The bottom panel is equivalent to fig. 4 of Mikkola et al. (2004).

3.3 Model 2

Our previous calculations clearly indicate that, in the case of 2002 VE₆₈, 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 in 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 VE₆₈ 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.

Fig. 9 confirms that 2002 VE₆₈ has been a quasi-satellite of Venus for some time although in these calculations it entered the quasi-satellite phase about 7000 yr ago, not 11 000 yr ago like in Model 1. In the time interval -7000 to $+1000$ 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 L_5 Venus Trojan location, quickly enters the horseshoe-like phase. It does not immediately become an L_4 Trojan like in Model 1. Consistently, Fig. 10 shows differences with respect to Fig. 7 although they

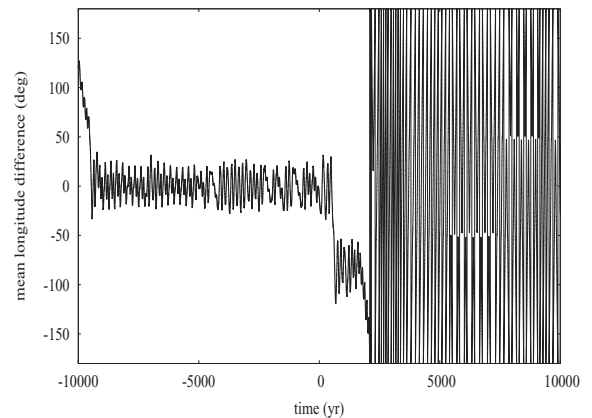


Figure 9. The mean longitude difference of 2002 VE₆₈ and Venus in the time interval $(-10\,000, 10\,000)$ yr from Model 2. In the time interval -7000 to $+1000$ yr from now the evolution of the mean longitude difference is very similar to that from Model 1 (see Fig. 6) but, after leaving the quasi-satellite dynamical state, the asteroid does not become a long-term Venus Trojan.

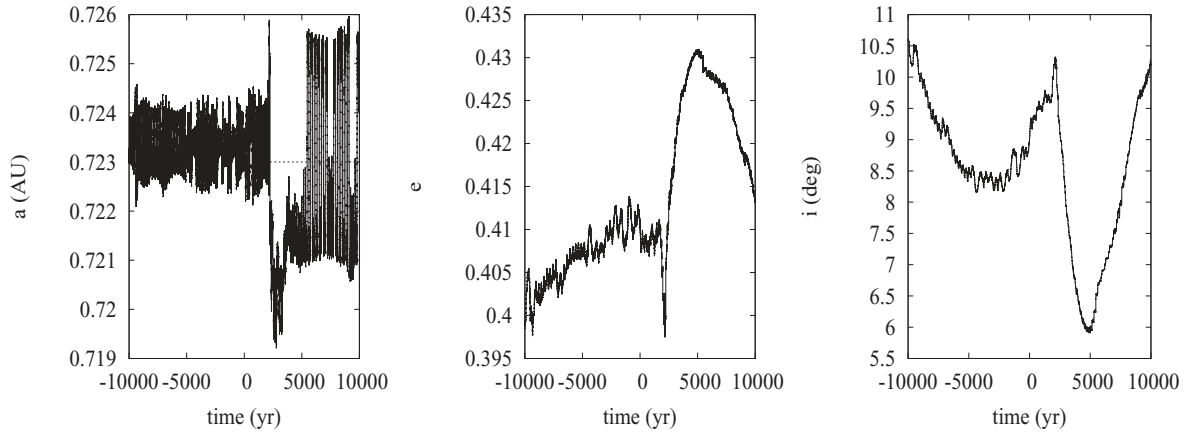


Figure 10. Orbital elements of 2002 VE₆₈ from Model 2.

exhibit similar behaviour in the time interval -7000 to $+1000$ yr from now. During the horseshoe-like phase, the semimajor axis remains oscillating (but with larger amplitude) around the value of the semimajor 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 VE₆₈ 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 VE₆₈ 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. Fig. 12 shows that the evolution of the mean longitude difference in the time interval -7000 to $+1000$ yr is very similar to those from Models 1 and 2 (see Figs 6 and 9), confirming again that 2002 VE₆₈ has been a quasi-satellite of Venus for a period of time but that it will soon leave the quasi-satellite phase for the L_5 Lagrangian point. The behaviour 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. Fig. 14 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 18000 yr in 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.

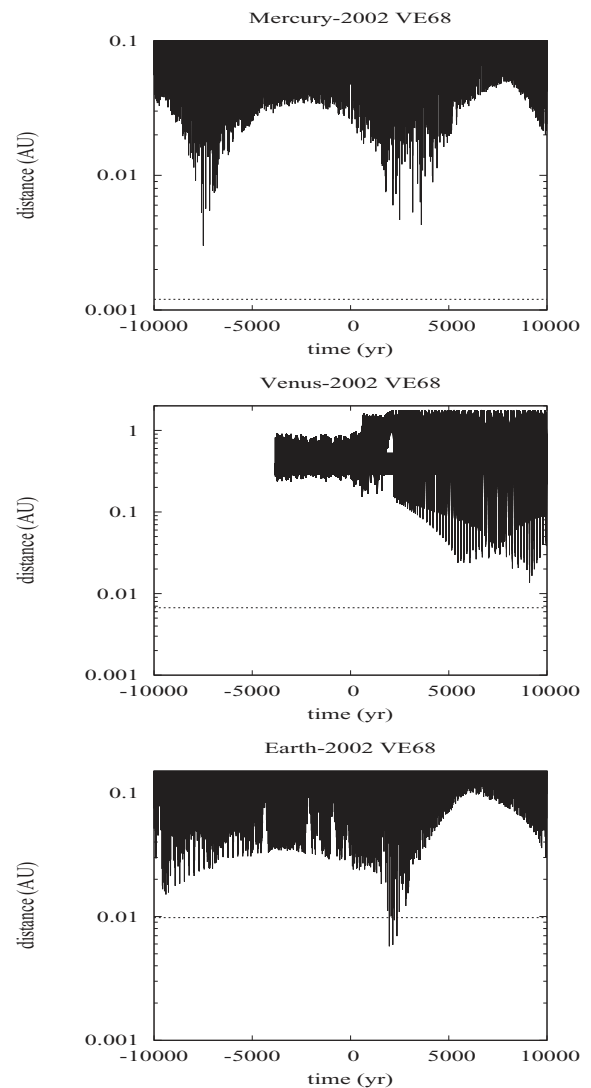


Figure 11. The distance of 2002 VE₆₈ from Mercury (top panel), Venus (middle panel) and the Earth (bottom panel) from Model 2. The middle panel is equivalent to fig. 3 of Mikkola et al. (2004). The bottom panel is equivalent to fig. 4 of Mikkola et al. (2004).

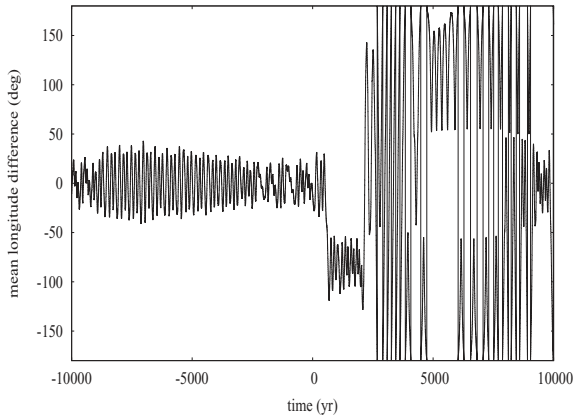


Figure 12. The mean longitude difference of 2002 VE₆₈ and Venus in the time interval (−10 000, 10 000) yr from Model 3, our most realistic model. In the time interval −7000 to +1000 yr from now the evolution of the mean longitude difference is very similar to that from Models 1 and 2 (see Figs 6 and 9) but, after leaving the quasi-satellite dynamical state, the asteroid follows a very complex evolution with multiple transitions between the various co-orbital resonant states.

4 DISCUSSION

The asteroid 2002 VE₆₈ 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 and 2002 VE₆₈ 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. Fig. 15 shows the evolution of the distance to the nodes of 2002 VE₆₈ 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 the 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.

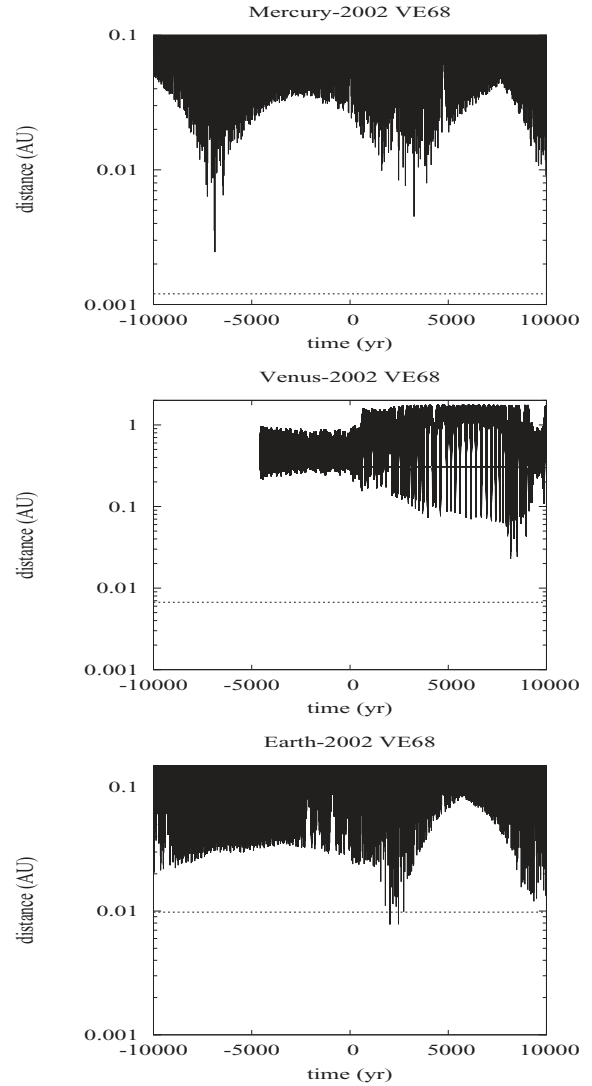


Figure 14. The distance of 2002 VE₆₈ from Mercury (top panel), Venus (middle panel) and the Earth (bottom panel) from Model 3. The middle panel is equivalent to fig. 3 of Mikkola et al. (2004). The bottom panel is equivalent to fig. 4 of Mikkola et al. (2004).

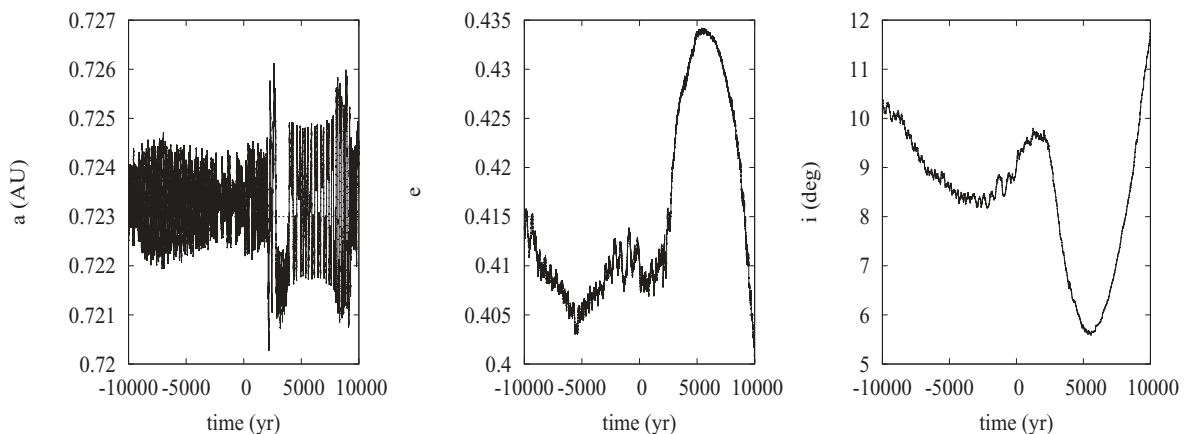


Figure 13. Orbital elements of 2002 VE₆₈ from Model 3.

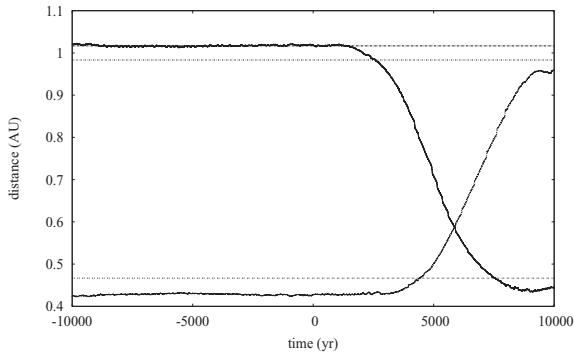


Figure 15. The distance to the descending (thick line) and ascending nodes (dotted line) of 2002 VE₆₈. The Earth’s aphelion and perihelion and Mercury’s aphelion distances are also shown. The distance of the descending node coincides almost perfectly with the Earth’s aphelion during the entire quasi-satellite phase. This figure is equivalent to fig. 5 of Mikkola et al. (2004).

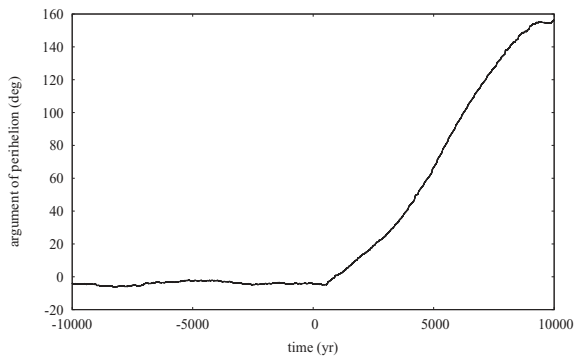


Figure 16. The argument of perihelion of 2002 VE₆₈. Its value decreases during the quasi-satellite phase at a rate of $\dot{\omega} = -0''.0005 \text{ yr}^{-1}$.

The object approaches the Earth in the vicinity of its descending node in November every eighth year. In fact, 2002 VE₆₈ 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 yr. 2002 VE₆₈ has a period of 0.6156 yr that is almost 8:13 (0.6154), so the Earth completes eight orbits around the Sun in the same amount of time the asteroid completes 13. But this is not all; 2002 VE₆₈ is also moving in a near 9:23 resonance with Mercury. 2002 VE₆₈ 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 the object moves in a 1:1 mean motion resonance, changes in the values of the semimajor 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 VE₆₈ is displayed in Fig. 16. During the quasi-satellite phase, its value decreases at a rate of $\dot{\omega} = -0''.0005 \text{ yr}^{-1}$. 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

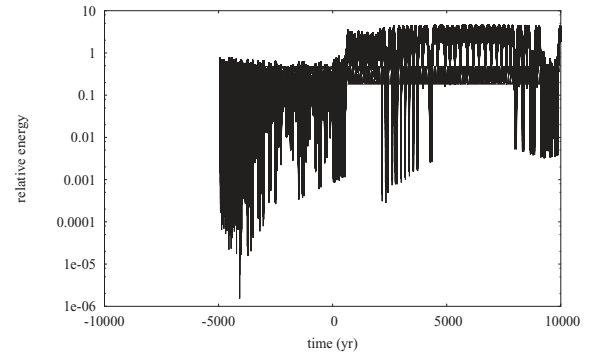


Figure 17. Total energy (specific orbital energy) of 2002 VE₆₈ relative to Venus. The quasi-satellite state, even if not bound (energy >0), is significantly less energetic than the other resonant states (Trojan or other).

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 VE₆₈ 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 VE₆₈ 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 -7000 to $+1000$ yr. The orbital behaviour on longer time-scales, even if not coincident, can also be discussed but in probabilistic terms. For example, 100 per cent 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 8000 – 7000 yr in the past for 70 per cent of the control orbits with the remaining 30 per cent experiencing the transition earlier than 8000 yr ago. Prior to the L_4 Trojan state, 60 per cent of control calculations were following horseshoe orbits, 20 per cent were in the quasi-satellite state, 10 per cent were in the L_5 Trojan state and the remaining 10 per cent 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 7500 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 0.037 82 au on 2018 November 4, 12:41 UT, will take place (the MPC¹⁰ quotes 0.037 64 au on 2018 November 4.90). Encounters that close to the Earth occur regularly and they have a periodicity of 8 yr. In fact, 2002 VE₆₈ was

¹⁰ <http://www.minorplanetcenter.net/iau/lists/PHACloseApp.html>

discovered during one of these close approaches, 2002 November 11. 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 2106 November 12 at 0.024 82 au. No encounters closer than 0.023 au will be recorded within the next 1000 yr.

As for the apparently battered surface of 2002 VE₆₈ we cannot avoid to speculate whether the relatively strong tidal forces generated during its frequent close fly-bies 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.

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 7000 yr, and it will remain in that phase for another 500 yr. Then it will move into a temporary tadpole orbit around the Venus L_5 Lagrangian point becoming a Trojan asteroid for about 700 yr to later transfer to the L_4 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 of 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 and 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, that it will leave its unusual dynamic status in a relatively short time-scale (about 500 yr) and that it went into its current state after a close encounter with the Earth about 7000 yr ago, although the actual time-scale for this event is less constrained in our calculations (7000–14 000 yr ago). We agree that the Earth has a dominant role in 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 the Earth's aphelion. They found that the e-folding time during the quasi-satellite phase was nearly 300 yr; our calculations gave ~ 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. A. Skiff in 2002 (Griesser et al. 2002) and subsequently identified as a quasi-satellite of Venus (Mikkola et al. 2004). This paper revisited the dynamical status of 2002 VE₆₈, numerically integrating its trajectory using updated ephemerides and analysing the results. We studied the orbit of 2002 VE₆₈ 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 VE₆₈ announced by Mikkola et al. (2004).
- (b) We confirm that 2002 VE₆₈ will leave its unusual dynamic status in a relatively short time-scale (about 500 yr).
- (c) We confirm that 2002 VE₆₈ went into its actual state after a close encounter with the Earth about 7000–14 000 yr ago.
- (d) Close approaches are possible both at perihelion (with Mercury) and aphelion (with the Earth). The Earth's are more important.
- (e) The influence of the Moon on the dynamics of 2002 VE₆₈ is not negligible as very close encounters with the Earth are possible.
- (f) 2002 VE₆₈ 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 yr. The next close approach to the Earth will take place on 2018 November 4 at 0.038 au.

Currently, the Earth has five known objects regarded as quasi-satellites: 3753 Cruithne (Wiegert, Innanen & Mikkola 1997), 2003 YN₁₀₇ (Brasser et al. 2004; Connors et al. 2004), (164207) 2004 GU₉ (Brasser et al. 2004; Connors et al. 2004; Wiegert et al. 2005; Mikkola et al. 2006; Wajer 2010), 2006 FV₃₅ (Mikkola et al. 2006; Stacey & Connors 2009; Wajer 2010) and 2010 SO₁₆ (Christou & Asher 2011). 2002 AA₂₉ will become a quasi-satellite of the Earth in the future (Connors et al. 2002). Venus has one, 2002 VE₆₈ (Mikkola et al. 2004). Jupiter has four known quasi-satellites (Kinoshita & Nakai 2007): 2001 QQ₁₉₉, 2004 AE₉, P/2002 AR₂ LINEAR and P/2003 WC₇ LINEAR-CATALINA, but new co-orbitals have recently been identified (Wajer & Królikowska 2012). A few hundred main-belt asteroids appear to be co-orbital (quasi-satellites in some cases) with (1) Ceres and (4) Vesta (Christou 2000; Christou & Wiegert 2012). Clearly the more objects identified in the quasi-satellite phase the better our understanding of their stability will be. Recognizing a variety of objects in the quasi-satellite state under different dynamical environments can only improve our knowledge of the overall processes that lead to the transformation of passing orbits into co-orbital ones and vice versa.

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