

Dynamical evolution of two near-Earth asteroids to be explored by spacecraft: (433) Eros and (4660) Nereus

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Abstract. We have studied numerically the dynamical evolution of the two near-Earth asteroids (433) Eros and (4660) Nereus, to be explored by planned space missions in the next decade, over a time scale of 2 Myr. For each real asteroid, we integrated a set of several initially “indistinguishable” orbits (*clones*), obtained either by small variations of the nominal initial conditions, or by using different computers (introducing different round-off errors). As for Nereus, its orbital evolution is typically dominated by Earth encounters, causing a random walk in semimajor axis. Protection mechanisms related to secular and mean motion resonances are often temporarily at work, but are not likely to increase much Nereus’ lifetime. According to our results, it is unlikely that this (C-type) NEA comes from a comet-like initial orbit, or at least that such a transition has occurred in the last ≈ 10 Myr. As for Eros, 5/8 clones always stay in the Mars-crossing, Amor-like region, but 3 of them become Earth-crossers within the 2 Myr of our integration time span, and indeed one of them was observed to hit the Earth after 1.14 Myr. Therefore an Earth impact by this 20-km sized NEA is unlikely but not impossible in the next $10^6 - 10^8$ yr. Eros probably reached its present orbit by a “slow-track” evolution dominated by Mars encounters, and is a comparatively old fragment originated by a large-scale collision occurred in the main belt.

Key words: celestial mechanics – meteors, meteoroids – minor planets – minor planets: individual: 433 Eros; 4660 Nereus

1. Introduction

Understanding the dynamical evolution of near-Earth Asteroids (NEAs) is important for several reasons. First, these objects, which have perihelion distances less than about 1.3 AU, can get close to the Earth, cross its orbit and hit our planet, representing a long-term danger for the biosphere and the human species

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(Chapman & Morrison 1994; Adushkin & Nemchinov, 1995). Their impact rates with the Earth (and the other inner planets) depend upon their orbital configuration, and can vary by orders of magnitudes for different orbital states and depending on the presence of a variety of “protection mechanisms” (Milani et al., 1990).

Secondly, NEAs represent the larger siblings of meteoroids and bolides, as well as of the very small objects (≈ 10 meters in size) recently discovered by the Spacewatch survey (Rabinowitz 1993, Rabinowitz et al. 1993). Their dynamical evolution can thus tell us much on the “demography” of the population of small interplanetary bodies which continuously interact with our planet, are observed with a variety of techniques and are often recovered and collected as meteorites (Ceplecha 1992, Jopek et al. 1995, Gladman et al. 1995, Bottke et al. 1995, Haack et al. 1995).

Thirdly, physical remote-sensing observations of NEAs have recently revealed a number of surprising features, such as a high metal abundance (Ostro et al. 1991), a “bifurcated” or contact-binary structure (Hudson & Ostro 1994, Ostro et al. 1995), and a tumbling rotational state (Harris 1994). Are these features related to the asteroidal vs. cometary origin of NEAs? or rather to their dynamical/collisional evolution *en route* to the inner planet region? As for NEAs of asteroidal origin, they are widely believed to be continuously injected into Earth-crossing orbits through a few different resonant channels, which collect fragments randomly ejected from main-belt asteroids as a consequence of energetic interasteroidal collisions (see e.g. Wetherill, 1985, 1987; Farinella et al., 1993a,b). Subsequently, these fragments undergo a fairly complex orbital evolution process, driven by mean motion and secular resonances, by non-resonant secular perturbations and by a sequence of close encounters with planets. Although this process has been studied in some detail in recent times, mainly by means of numerical integrations of the motion of real and fictitious minor bodies under the gravitational influence of the Sun and the planets (Milani et al., 1989; Farinella et al., 1994; Froeschlé et al., 1995; Michel et al. 1996; Michel and Thomas, 1996), the results have shown a puzzling variety of behaviours. Thus our understanding of the dynamical

Table 1. Starting osculating orbital elements of (4660) Nereus and three “clone” orbits. The name of the asteroid is followed by that of the orbital element which has been changed by a small amount.

Epoch 2449600.5 J.D. Ecliptic 2000.0 Equinox 2000.0 The elements were taken from the Ephemerides of Minor Planets 1994.						
Body Name	ω	Ω	i	e	a (AU)	M (mean anomaly)
(4660) Nereus	157°.77303	314°.85246	1°.42495	0.3602636	1.4896013	342°.61881
Nereus a	157°.77303	314°.85246	1°.42495	0.3602636	1.4906013	342°.61881
Nereus e	157°.77303	314°.85246	1°.42495	0.3612636	1.4896013	342°.61881
Nereus i	157°.77303	314°.85246	1°.43495	0.3602636	1.4896013	342°.61881

Table 2. Starting osculating orbital elements of (433) Eros and three “clone” orbits. The name of the asteroid is followed by that of the orbital element which has been changed by a small amount.

Epoch 2448600.5 J.D. Invariable Plane Equinox 1950.0 The elements were taken from the Ephemerides of Minor Planets 1991.						
Body Name	ω	Ω	i	e	a (AU)	M (mean anomaly)
(433) Eros	180°.69953	298°.82388	12°.35003	0.2228695	1.4583155	209°.78952
Eros a	180°.69953	298°.82388	12°.35003	0.2228695	1.4683155	209°.78952
Eros e	180°.69953	298°.82388	12°.35003	0.2238695	1.4583155	209°.78952
Eros i	180°.69953	298°.82388	12°.36003	0.2228695	1.4583155	209°.78952

cal transfer process from the main belt to the inner planets is still poor, and this hinders our ability to interpret the physical properties of NEAs in terms of those of their asteroidal parent bodies.

A further motivation to study the dynamical evolution of NEAs has arisen recently. Fairly soon, a couple of these bodies will be visited by dedicated space missions, which will collect data from their vicinity over extended periods of time. The *NEAR* mission, launched by NASA in early 1996 as the first spacecraft of the new “Discovery” program, will carry out in 1999 a year-long rendezvous with (433) Eros, the second-largest NEA, and will make comprehensive scientific measurements of its surface composition, physical properties, geology and internal structure (Chapman 1995; Cheng 1995; Farquhar et al. 1995). A similar mission, but including sample return, is being planned by the Japanese Institute of Space and Astronautical Science (Kawaguchi et al. 1994) to visit in 2003 (4660) Nereus, previously named 1982 DB, perhaps the known NEA which currently undergoes most frequent close approaches to the Earth (Milani et al. 1990). Although, as we shall see, dynamical studies cannot reconstruct in a deterministic way the past (or future) orbital evolution of NEAs, whose dynamics is strongly chaotic and therefore unpredictable over times $\approx 10^3$ yr or longer, even statistical conclusions on the past orbital history of these bodies would be valuable to interpret their surface features and understand their origin. For instance, is there any chance that these NEAs had in the past a Jupiter-crossing, comet-type orbit? may their formation be related to impact break-up events occurred in the inner asteroid belt and recorded there by the formation of a dynamical family? for how long is it likely that their aphelia have stayed inside the main belt, exposing their surface to an impact flux much higher than in the inner planet zone?

(433) Eros was discovered by G. Witt in 1898, and it has been the first known planet-crossing (Mars-crossing) asteroid. It belongs to the Amor group, i.e. its current semimajor axis is > 1 AU and its perihelion distance is $1.017 < q < 1.3$ AU.

Therefore, it does not currently cross the Earth’s orbit. In 1975, it approached Earth at 0.15 AU and was observed by a variety of techniques (including radar). This led to a comparatively detailed knowledge of its physical properties. (433) Eros is an S-type asteroid, with a mean diameter of about 20 km, more than twice the largest current Earth-crosser [(1866) Sisypheus, about 8 km across] and about half the largest Amor object [(1036) Ganymed, 38 km in mean diameter]. Its surface is probably covered by a regolith, and its global shape is highly nonspherical, with approximate triaxial dimensions of $36 \times 15 \times 13$ km. Its rotation period is 5.27 hr. These properties look fairly similar to those of most asteroids of similar size orbiting in the inner portion of the main belt, such as (951) Gaspra, imaged by the *Galileo* probe in 1991. If Eros is a fragment from a disruptive collision, the latter event had to be very energetic and to occur near a resonant “strip” of the orbital element space. Indeed, numerical simulations of the asteroid collisional evolution process (Menichella et al. 1996) show that the delivery of such sizeable fragments from the main belt should be a rare occurrence, and that it is unlikely that it took place less than ≈ 100 Myr ago.

As for (4660) Nereus, it was discovered by E. Helin in 1982. It is classified as an Apollo asteroid, i.e. its current semimajor axis is more than 1 AU but its perihelion distance is < 1.017 AU. It is one of the few C-type NEAs, its diameter is about 1 km, but little else is known about its physical properties. The dark, probably carbon-rich surface would be consistent with it being either a fragment from a C-type main-belt parent asteroid, or an extinct comet nucleus. Its low orbital inclination is the cause both of its frequent close approaches to the Earth (the next one will occur in 2002, with a minimum distance of 0.029 AU) and of its comparatively easy accessibility from our planet.

In this paper, we are going to present a numerical study of the long-term dynamical evolution of the two NEAs described above. The numerical character of our study is due to the fact that, for asteroid orbits with semimajor axes less than 2 AU, perturbations by and encounters with the terrestrial planets nor-

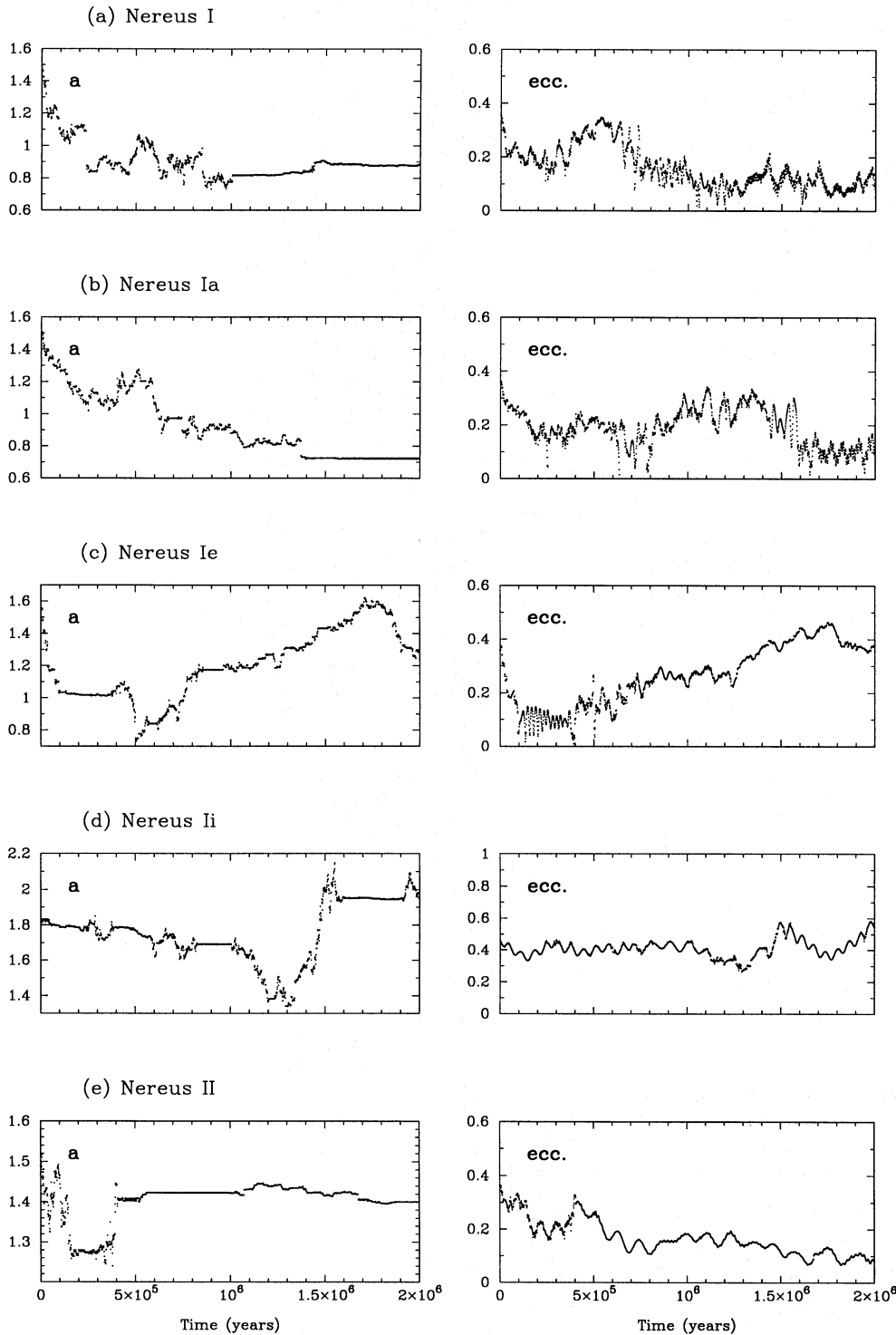


Fig. 1a–e. The evolutions of the semimajor axis (a , in AU) and eccentricity of the five Nereus clones over 2 Myr.

mally play an essential role, so making impossible the use of the analytical theories developed to study the dynamics of main-belt asteroids (for which outer planets only are important). Note that since orbits of NEAs are strongly chaotic (see Sect. 2), numerical integrations cannot provide quantitative information about the past and future evolution of any specific, real object; however, they allow one to study the qualitative behaviour of the orbits and the main dynamical mechanisms at work, in a region

where these are not known yet on timescales of millions of years (and longer). We recall that Milani et al. (1989) carried out numerical integrations of many NEA orbits over 2×10^5 years and found some objects with semimajor axes $a < 2$ AU displaying intriguing secular trends in eccentricity and/or inclination – but the integration time span was too short to obtain an estimate of the relevant time scales and to identify the responsible mechanisms. More recently, Froeschlé et al. (1995) and Michel and

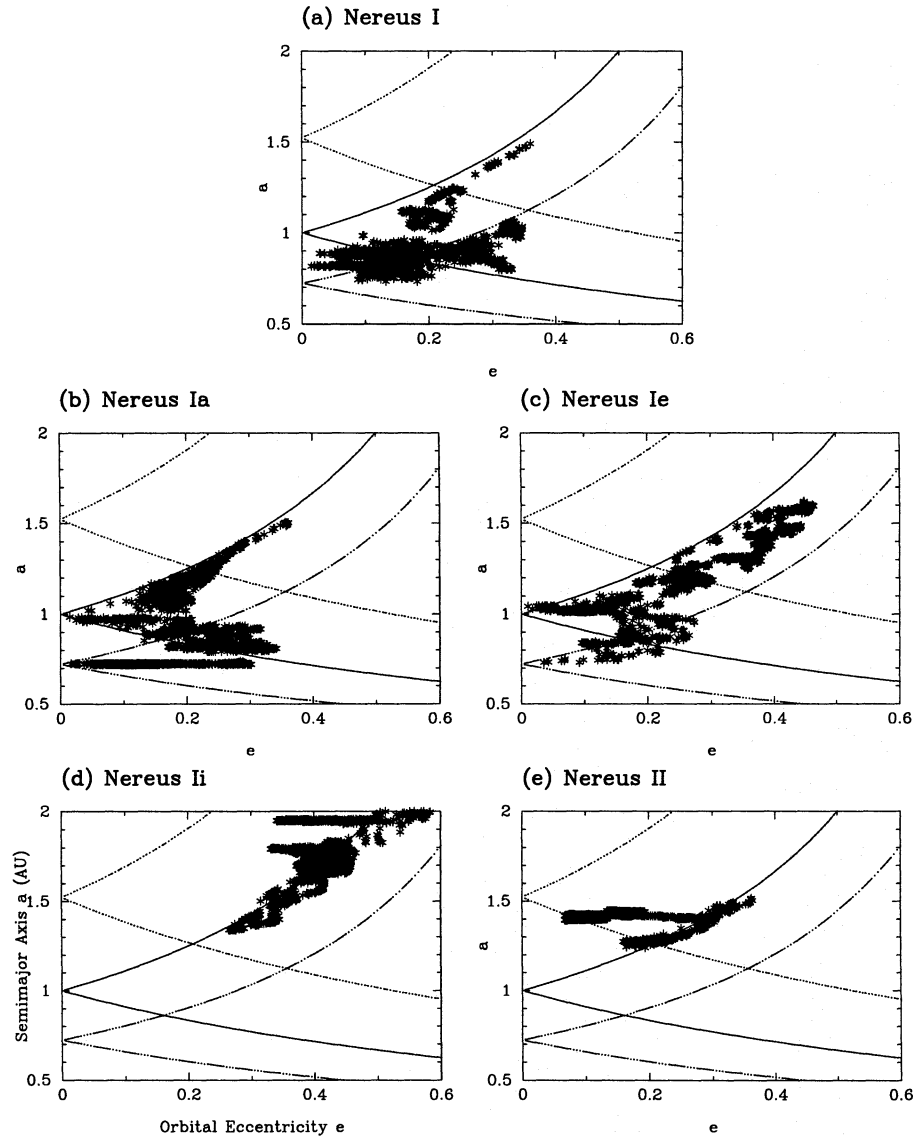


Fig. 2a–e. The evolutions of the five Nereus clones in the semimajor axis (a , in AU) vs. eccentricity (e) plane. The dashed, full and dotted lines correspond to perihelion and aphelion distances equal to the semimajor axes of Venus, the Earth and Mars respectively.

Thomas (1996) numerically integrated several objects in this region over a time span of the order of 1 Myr, and found that both the main secular resonances with the outer planets (Knežević et al. 1991) and the Kozai resonance (Kozai 1962) can affect the orbital evolution in a significant way. Mean motion resonances had already been found by Milani et al. (1989) to cause either strongly chaotic behaviour, or protection mechanisms preventing close encounters (and impacts) with the planets. Thus, we shall devote here a specific attention to all the resonant effects influencing the orbits resulting from our integrations.

The remainder of this paper is organized as follows. The initial conditions of the two asteroids and their “clones”, as well as the numerical method adopted in our work, are presented in Sect. 2. In Sect. 3 we describe the results and provide, for each body, an overview of the main dynamical mechanisms at work over the 2 Myr time span of the integration. The implications of those results and some open problems are summarized in Sect. 4.

2. Numerical method and initial conditions

It is well known that the orbits of planet-crossing objects, including both NEAs and comets, are very chaotic, with Lyapunov divergence times $t_L \approx 10^2$ yr (Whipple 1995, Tancredi 1995), owing to the sensitive dependence of the orbital changes caused by close planetary encounters on the pre-encounter orbital elements. A consequence of this is that the dynamical evolution of such objects cannot be studied by analytical methods, since orbital crossings and encounters would introduce singularities in the series developments which are used to represent the solutions of the equations of motion. Thus we decided to study the long-term dynamical evolution of (433) Eros and (4660) Nereus by purely numerical integrations of the N-body gravitational problem.

These integrations were carried out with a Bulirsch-Stoer variable step-size technique (Stoer and Bulirsch 1980), optimized for dealing accurately with close encounters, and also adapted by us for recording the miss distances corresponding to

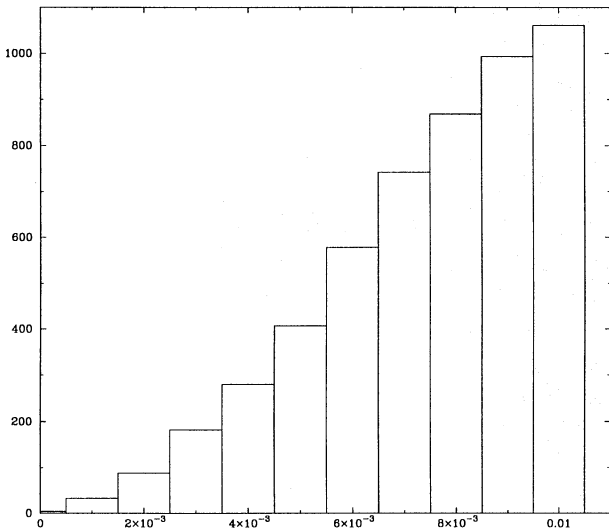


Fig. 3. Histogram of the cumulative number of close approaches of Nereus to the Earth vs. minimum distance (in AU). The five Nereus clones are considered together (so the total time span during which the encounters have been recorded is 10 Myr).

the encounters despite the discrete time steps used by the program to compute the orbit and output the corresponding position and velocity vectors. This was done in the following way. Every time the minor body approached a planet to less than $3R_i/2$, R_i being the radius of the planet's gravitational sphere of influence (equal to $a_p(M_p/M_\odot)^{2/5}$, where a_p is the semimajor axis of the planet, M_p its mass and $M_\odot$ the solar mass; see Bertotti & Farinella 1990, Ch. 18), we computed the pericentre distance of the two-body hyperbolic orbit approximating the planetocentric motion of the minor body. If the distance to the planet was found to be $< 3R_i/2$ over a sequence of successive time steps, the minimum value of the pericentric distance during the sequence was assumed to be the miss distance of the encounter along the true orbit.

We adopted a purely gravitational model of the Solar System, including all the planets except Pluto and Mercury (the mass of Mercury being added to that of the Sun), with the Earth-Moon pair considered as a single body. The integration time always spanned 2 Myr in the future.

As we already noted, the strongly chaotic nature of the orbits implies that the results of the numerical integrations cannot be seen as deterministic predictions of the evolution of the real objects, at least over times much longer than the Lyapunov time t_L . In fact, it is easy to show that planet-crossing orbits are very sensitive not only to the chosen initial conditions, but also to the assumed physical model of the Solar System, to the integration algorithm and to the round-off features of the computer used to run the integrations. Introducing small changes to any of these options implies that after a time span of several times t_L , the computed orbits completely “lose memory” of their common origins. They are just “possible evolutions”, useful to identify the most important dynamical mechanisms which *may* affect the real orbit, or to make statistical estimates on the ob-

ject's lifetime, encounter rate and so on. Thus, for both NEAs considered in this work, we studied not only the *nominal object* corresponding to the initial conditions listed in the asteroid ephemerides, but also a sample of *clones*, i.e. of initially “indistinguishable” orbits obtained either by small variations of the nominal initial conditions, or by using different computers (implying different round-off errors) to perform the actual integrations. For each NEA, three clones were obtained by changing by small amounts (one at a time) the starting semimajor axis, eccentricity and inclination (see Tables 1 and 2). Moreover, in the case of (4660) Nereus the nominal orbit was integrated on two different computers (which we refer to as I and II), so we obtained the dynamical evolution of five clone orbits overall. As for (433) Eros, the first integration we carried out showed a surprising result, namely an actual collision with the Earth after only about 1 Myr. To check whether this was a coincidence, we tried to further improve our statistics by integrating both the nominal Eros and its three varied orbits on the two computers, thus obtaining overall eight clones representing possible dynamical evolutions of this object.

3. Results

In this section, we will analyse and discuss in some detail the different dynamical features of the orbits resulting from our numerical integrations. We will look in particular at the frequency and effectiveness of close approaches with planets, at the presence of secular resonances and at the possible protection mechanisms which prevent close approaches, resulting from either a mean motion resonance with an inner planet or a libration of the perihelion argument ω of the small body's orbit (i.e., the Kozai resonance).

Concerning secular resonances, which are resonances between the precession rates of the asteroid's orbit and the precession rates of the planets, we recall that their effects and locations have been well studied in the main asteroid belt, where no close approaches with planets occur. There, all the three main secular resonances have a significant effect on the orbital elements of small bodies. The ν_6 resonance (which corresponds to the libration of the critical angle $\varpi - \varpi_S \approx 0^\circ$, ϖ and ϖ_S being the perihelion longitudes of the body and Saturn respectively) provides the most effective mechanism for the transport of material to the inner planet zone, as it can pump up the eccentricity from 0 to almost unity. Conversely, the ν_5 resonance (involving the perihelion of Jupiter instead of Saturn) increases the eccentricity only to moderate values, resulting into Mars-grazing or Mars-crossing orbits, whereas the ν_{16} resonance (involving the precession of the nodes of the asteroid and Saturn) can yield large increases in inclination but no dramatic changes in the eccentricity. On the other hand, inside the main belt, i.e. for $a < 2$ AU, when the inner planets are neglected no main secular resonance is present; nevertheless, numerical integrations including the inner planets have shown that effects due to secular resonances show up for NEAs with $a < 2$ AU (Froeschlé et al. 1995). Thus we have carefully monitored all the main secular critical arguments in analysing the outputs of our integrations.

Table 3. Dynamical mechanisms affecting the orbits of (4660) Nereus and its *clones*: Nereus I and II correspond to the “nominal” orbit integrated on two different computers; a , e , i label the clones for which the corresponding starting elements were changed; CA is the abbreviation for close approaches; (V), (E) and (M) correspond to Venus, Earth and Mars, respectively; the unit of time (t) is 10^5 years. The secular resonances are identified by Williams’ (1969) notations. The last column lists the protection mechanisms found to be at work: the argument of perihelion ω (in brackets the centre of libration) for the Kozai resonance; the involved commensurability and planet for the mean motion resonances.

Body	Osculating Elements	Close Approaches	Secular Resonances	Protection Mechanisms
Nereus I	a : decreasing random-walk then almost constant e , i : changed by CA	numerous deep then shallow with V and E	$t > 10$: alternator in ν_6 , ν_5	
Nereus Ia	a : random-walk or almost constant e : secular trend, secular increase i : changed by CA secular increase	Numerous deep with E Some deep with V, M	$t < 2$: ν_2 , ν_3 , ν_5 $15.5 < t < 16.5$: ν_2 , ν_3 , ν_4 , ν_6 $14 < t < 18$: ν_{16} $t > 18$: ν_{13} , ν_{14}	$\omega(0^\circ)14 < t < 16$ $1/1$ (V) $t > 16$
Nereus Ic	a : changed by CA e : secular increase i : coupled oscillations with e changed by CA	numerous with E, M some deep with V	$t < 1$: ν_2 , ν_3 , ν_4 , ν_5 $10.5 < t < 15$: ν_5 $t > 14.5$: ν_3 $14.5 < t < 16$: ν_2	$\omega(180^\circ)1.5 < t < 4$ $11/14$ (E) $8.5 < t < 10$
Nereus Ii	a : changed by CA e : short period oscillations i : short period oscillations	numerous deep with E, M	$7.5 < t < 16$: ν_4 $12.5 < t < 114.5$: ν_3 $12.5 < t < 15$: ν_2 $t > 16$: very close to ν_6	$5/11$ (E) $7.5 < t < 11$
Nereus II	a : changed by CA e : secular decrease i : large oscillations, secular increase	Some shallow with E Numerous shallow with M	$t < 4.1$: ν_4 $3.5 < t < 7$: ν_{16} $7.2 < t < 11$: ν_2 $12.2 < t < 14.5$: ν_2 $t > 12$: ν_{14} $t > 13$: ν_{13}	

Table 4. Maximum and minimum values of semimajor axis a , eccentricity e and inclination i (with respect to the ecliptic J2000) reached during the Nereus integrations. The Table also gives the closest approach distances to Venus, the Earth and Mars, and the fractions of time spent in an Earth-crossing state (f_1) and with the aphelion distance exceeding 1.7 AU (f_2).

Body	a_{min} (AU)	a_{max}	e_{min}	e_{max}	i_{min} ($^\circ$)	i_{max}	min. dist. (AU)	f_1 (%)	f_2 (%)
Nereus I	0.733	1.490	0.015	0.360	0.094	13.430	5.310×10^{-4} (V) 4.072×10^{-4} (E) 2.596×10^{-3} (M)	53.63	1.1
Nereus Ia	0.720	1.505	0.015	0.362	0.103	21.277	1.684×10^{-4} (V) 1.699×10^{-4} (E) 1.051×10^{-3} (M)	66.68	2.75
Nereus Ic	0.731	1.621	0.010	0.464	0.524	12.5657	4.209×10^{-5} (V) 1.044×10^{-3} (E) 5.125×10^{-4} (M)	94.9	37.07
Nereus Ii	1.339	2.148	0.265	0.583	0.187	9.235	0.131 (V) 8.999×10^{-4} (E) 1.036×10^{-3} (M)	54.58	99.9
Nereus II	1.234	1.517	0.067	0.364	0.202	16.926	0.239 (V) 1.057×10^{-3} (E) 8.413×10^{-4} (M)	16.34	16.89

We hope that this kind of numerical exploration will lead soon to determine the location and strength of the most important secular resonances also in the inner Solar System.

We will discuss separately the results concerning (4660) Nereus and (433) Eros. For each asteroid, the main results on its evolution (and those of its *clones*) are summarized in two tables: one gives the observed trends in semimajor axis (a), eccentricity (e) and inclination (i), and lists the main dynamical mechanisms found to be at work during a significant part of the integration time span; another table gives the extrema of the osculating elements (i.e., the maximum amplitude of their variations), the closest-approach distances to the terrestrial planets (Venus, the Earth and Mars), and the fractions of time (f_1 and f_2 , respectively) spent by the minor body in an Earth-crossing orbit, having perihelion (q) and aphelion (Q) distances such as

$q = a(1 - e) < 1.017$ AU, $Q = a(1 + e) > 0.983$ AU, or with the aphelion farther from the Sun than the inner edge of the main asteroid belt ($Q > 1.7$ AU). The latter data are useful to estimate for how long, on average, the objects can have close encounters (or collisions) with the Earth, and can collisionally interact with main-belt asteroids.

3.1. (4660) Nereus

The main results for Nereus are summarized in Tables 3 and 4. Looking at both Tables, it is apparent that all the orbits undergo close approaches (CA) to the Earth and Mars and some of them also to Venus. These CA may be either deep or rather shallow, depending on the presence of a protection mechanism (see Sect. 3.1.2) and on the configuration of the orbit with re-

Nereus Ie

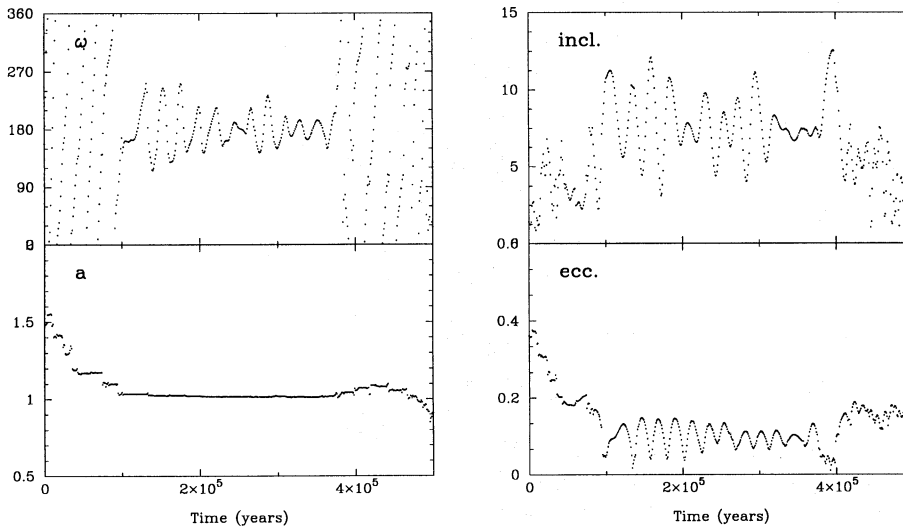


Fig. 4. Evolution of the semimajor axis (in AU), inclination (degrees), eccentricity and argument of perihelion (ω , in degrees) of Nereus Ie during the first 5×10^5 yr of our integration. The libration of ω and the related oscillations of the eccentricity and inclination are characteristic of the Kozai resonance.

spect to the planets. Some orbits also show secular trends in eccentricity and inclination, related to the occurrence of a secular resonance. The three main dynamical mechanisms affecting the orbital evolutions are now discussed separately.

3.1.1. Close approaches with planets

As shown in Fig. 1, all the orbits are dominated by CA with the inner planets, at least over a significant portion of the total time span. Indeed their semimajor axis undergoes a series of “chaotic jumps” associated with close planetary encounters, which change the orbital elements of the minor body over a very short interval. It is also interesting to note that the eccentricity, though affected by encounters, shows quasi-periodic changes due to other causes, which leave the semimajor axis unaffected. In Fig. 2, the evolution of the orbits is plotted in a a vs. e diagram. The dashed, full and dotted lines correspond to the perihelion and aphelion distances equal to the semimajor axes of Venus, the Earth and Mars, respectively, namely to quasi-tangent orbital configurations. It is apparent that CA with Earth play the dominant role: the bodies spend most of the time inside the Earth-crossing region delimited by the two full lines, and often the evolution occurs roughly near the curves corresponding to a constant value of the Tisserand invariant with respect to the Earth (which lie inside and nearly parallel to the tangency lines, see Michel et al. 1996). This also explains the correlation between the time series of a and e apparent in Fig. 1 especially for Nereus Ia and Ie, because for this type of near-tangent orbits the constancy of the Tisserand invariant is approximately equivalent to that of the perihelion or aphelion distance, which stays close to that of the dominant perturbing planet (in most cases the Earth). In Fig. 1, it is also interesting to note that the semimajor axes of Nereus I and II show some prolonged periods of quasi-constancy, which are not due to protection mechanisms related to resonances, but simply to the fact that for some time secular

perturbations can cause the asteroid’s perihelion or aphelion to decouple from the orbits of the Earth and Venus, due to temporarily small eccentricity values, so no deep close encounter can take place.

The closest approach distances to the Earth during the 2 Myr integration time span range from 1.7×10^{-4} AU (Nereus Ia) to 1.04×10^{-3} AU (Nereus Ie). Some deep CA ($\approx 10^{-4}$ AU) to Venus occur for Nereus I, Ia and Ie, whereas Nereus II and II stay always far from this planet (more than 0.1 AU). Nereus Ie actually grazes Venus at $t \approx 5 \times 10^5$ yr, at an altitude of only 250 km above the surface (see Table 4). As a consequence of this very deep encounter, the semimajor axis suddenly drops by 0.13 AU. All the clones also undergo deep CA to Mars. This holds in particular for Nereus Ie and II, which reach frequently minimum distances from Mars $< 10^{-2}$ and 10^{-3} AU, respectively. However, due to the small mass of this planet, these CA are less effective in changing the orbit than those with the Earth and Venus.

In order to estimate the collision probability of Nereus with the Earth, we have calculated for all the five clones together the cumulative number of close encounters recorded during the integrations, with minimum approach distances smaller than a given set of values. As shown in Fig. 3, up to about 3×10^{-3} AU, the histogram is fitted well by a parabola, i.e., the number of encounters is approximately proportional to the square of the chosen threshold distance. For larger closest-approach distances, the trend becomes linear, due to the fact that most encounters occur at very low mutual inclinations, and therefore a two-dimensional encounter geometry is a better approximation. If we extrapolate the quadratic trend down to the radius of the Earth’s impact cross-section (about $1.5R_{\oplus}$ due to gravitational focusing of projectiles coming with typical speeds “at infinity” of about 10 km/s), we obtain a collisional lifetime of about 110 Myr. Note that this value is about an order of magnitude larger than that obtained by Milani et al. (1990, Table IV), from their

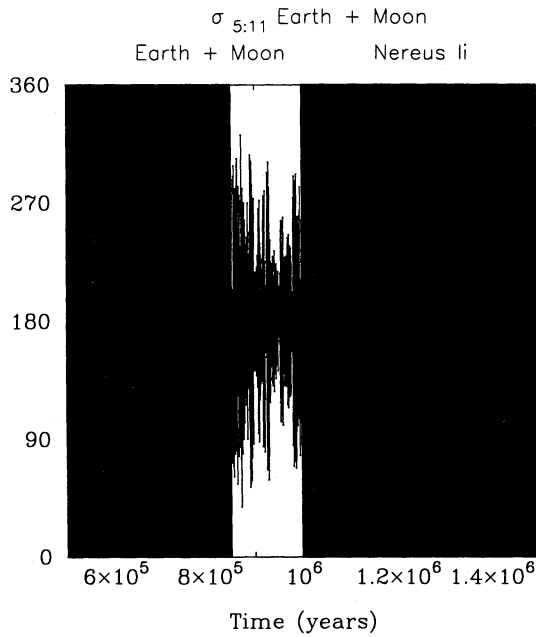


Fig. 5. The temporary libration about 180° of the critical argument $\sigma_{5/11}$ of the 5/11 mean motion resonance with the Earth, affecting Nereus II.

close encounter data base spanning 0.2 Myr only. This discrepancy is mainly due to the fact that the current inclination of Nereus is much smaller than the average value over 2 Myr (for all the five clones); moreover, during our integrations we found that for a significant fraction of the time protection mechanisms were at work, preventing close encounters from occurring at all (in the Milani et al. case, this occurred only shortly before the end of the integration). Thus our results indicate that anomalous collision probabilities with the Earth, such as found by Milani et al. for Nereus, may just be the outcome of peculiar orbital configuration, unlikely to last for millions of years. Actually, our estimated Earth impact lifetime $\approx 10^8$ yr for Nereus is close to the average value for all the known Apollo-type objects, according to the results of Bottke et al. (1994).

Table 4 shows that only for 4/5 Nereus clones the fraction of time f_1 spent in the Earth-crossing state is significantly lower than unity. Note that for two Nereus clones (I and Ia), when their orbits are not Earth-crossing it is because they have evolved in a state where they lie completely inside the Earth's orbit, with $Q < 0.983$ AU. On the other hand, the fraction of time f_2 spent with the aphelion in the main belt is basically unpredictable, ranging from 1.1% to 99.9% depending on the body. This means that it will be very difficult to infer Nereus' age from observations of the cratering record on its surface, as the projectile flux hitting it in the last few Myr is highly uncertain. Actually, Bottke et al. (1994) have found that the collisional lifetime of a typical km-sized NEA decreases by about two orders of magnitude when the aphelion distance becomes large enough to have it exposed to the main-belt projectile population (see also Farinella & Davis 1994).

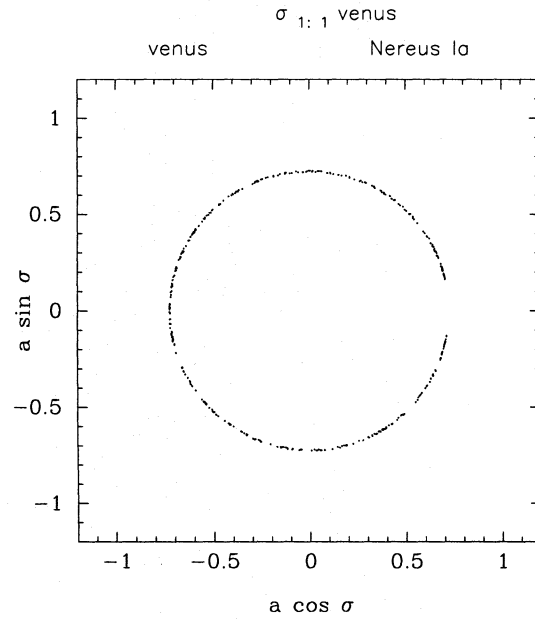


Fig. 6. The horse-shoe orbit with respect to Venus found for Nereus Ia, over 4×10^5 years. Polar coordinates in this diagram correspond to the semimajor axis a in AU and the librating critical argument $\sigma_{1/1}$ of the 1/1 resonance with Venus.

3.1.2. Protection mechanisms

Bodies Nereus Ia, Ie, II are temporarily protected from CA with the inner planets (see Table 3). As a consequence, during periods of time ranging from 1.5×10^5 yr (Nereus Ie) to 4×10^5 yr (Nereus Ia), the orbits evolve along a narrow horizontal strip in the (a, e) plane, namely the semimajor axis stays almost constant, even though the eccentricity may vary in a significant way and the perihelion/aphelion may cross the 1 AU line (see Fig. 1). This behaviour is a diagnostic of a resonance, either the Kozai secular resonance or a mean motion resonance with a terrestrial planet, even of high order (up to 6). Milani et al. 1989 grouped the objects locked in these two types of protecting resonances in the Kozai and Toro classes, respectively.

During at least 2×10^5 years (see Table 3), two Nereus clones (Ia, Ie) are locked in the Kozai resonance, with the argument of perihelion ω librating around 0° or 180° (Fig. 4), and with large coupled oscillations of the eccentricity e and the inclination i (e being minimum when i is maximum and *vice versa*). As explained by Michel and Thomas (1996), due to the libration of ω around 0° or 180° , the apsidal and nodal lines remain close to each other, and the orbit intersects the plane of the Earth's orbit near its perihelion or aphelion, which are both quite far from 1 AU. Hence, while the bodies stay in the Kozai resonance, their orbits almost never cross that of the Earth.

A different protection mechanism results from a mean motion resonance locking between the mean longitude of the body and that of a planet. We recall that a i/j mean motion resonance with a planet corresponds to a libration of the critical argument $\sigma_{i/j} = i\lambda - j\lambda_p + (i-j)\varpi$ around a constant value (here λ and

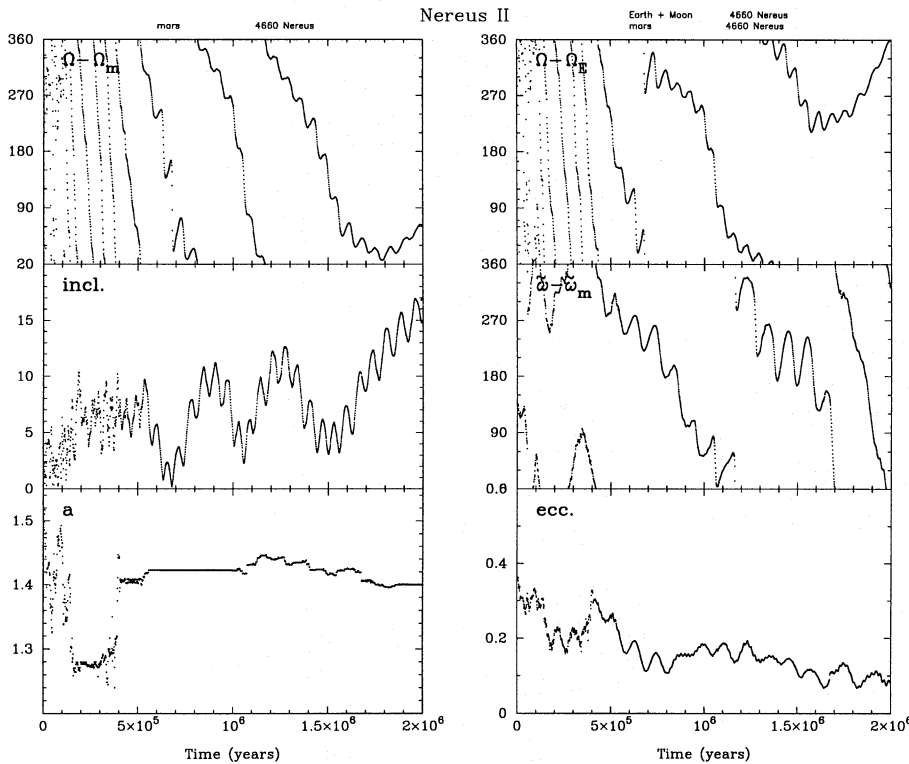


Fig. 7. Evolution of the orbital elements of Nereus II over 2 Myr. Besides semimajor axis, eccentricity and inclination, the figure shows also the three critical arguments ($\varpi - \varpi_M$, $\Omega - \Omega_M$ and $\Omega - \Omega_E$) of the ν_4 , ν_{14} and ν_{13} secular resonances (ϖ_M being the perihelion longitude of Mars, Ω_M and Ω_E the longitudes of the node of Mars and the Earth, respectively).

ϖ are the mean longitude and the longitude of perihelion of the asteroid, while λ_p is the mean longitude of the planet). Clones Ie and Ii are temporarily locked in the 11/14 and 5/11 mean motion resonances with the Earth, respectively, over time spans of a few times 10^5 yr. During the resonance locking, a oscillates around the value corresponding to the centre of the resonance, with an oscillation period equal to the libration period of the critical argument σ . As an example, Fig. 5 shows the temporary libration around 180° of $\sigma_{5/11}$ in the case of Nereus Ii. We recall that Milani et al. (1989, 1990) also found Nereus protected from close Earth encounters near the end of their integration, and eventually identified the 8/19 resonance with the Earth as the responsible dynamical mechanism.

The behaviour of Nereus Ia is a very interesting one. Up to 1.4 Myr, the orbit is dominated by CA, mainly with the Earth (see Figs. 1, 2). Then the body gets locked in the Kozai resonance for almost 2×10^5 years, and just afterwards it becomes trapped in the 1/1 mean motion resonance with Venus. Then, until the end of the 2 Myr integration time span, the semimajor axis oscillates around that of Venus (Figs. 1, 2) with an amplitude of $\approx 3.5 \times 10^{-3}$ AU. The critical argument $\sigma_{1/1}$ librates around the unstable Lagrangian point L_3 at 180° (see Fig. 6); its libration amplitude is very large, i.e. the body comes quite close to Venus (at $\sigma = 0^\circ$), but never enough to suffer destabilizing close encounters for at least 4×10^5 years. This behaviour corresponds to an unusually long-lived “horse-shoe” orbit.

Mikkola and Innanen (1992) have studied the stability of tadpole and horse-shoe orbits in both the outer and the inner solar system, performing suitable numerical integrations of test particles. Taking into account the planets from Mercury to Sat-

urn, they found that horse-shoe and tadpole orbits with Venus and the Earth stayed stable during their whole 2.25 Myr integration time span. This remarkable stability was confirmed by a simple analytical model. Previous numerical studies (Everhart, 1973; Hollabaugh & Everhart, 1973; Dermott & Murray, 1981) had already found similar results, but with shorter time scales or less realistic dynamical models. Such trappings into the 1/1 resonance with a terrestrial planet have also been recently reported in Marzari & Vanzani (1994), who studied the motion of dust particles affected by the Poynting-Robertson and solar wind drag effects and found an upper limit to the dynamical lifetime of “horse-shoe” orbits of $\approx 10^5$ years. All these studies, however, have been carried out using fictitious test particles, starting very close to the region of interest at the beginning of the integrations, whereas our Nereus Ia orbit was a typical NEA orbit, starting in a region of the phase space dominated by close encounters. Note that, Milani et al. already found that the asteroid (2063) Bacchus was protected from close approaches by a 1/1 resonance with the Earth, but for a shorter time span (about 43,000 years). We plan to further study this peculiar type of NEA orbits in a forthcoming paper, also to assess whether such bodies may exist and be discovered in the real Solar System.

3.1.3. Secular resonances

As we discussed in Sect. 2, our results are not sufficient to study in detail the location and effects of secular resonances with involving the inner planets. However, during the integration time span all the Nereus clones cross or stay temporarily in apsidal (ν_2 , ν_3 , ν_4) or nodal (ν_{12} , ν_{13} , ν_{14}) secular resonances with Venus, the Earth and Mars (see Table 3); the respective critical

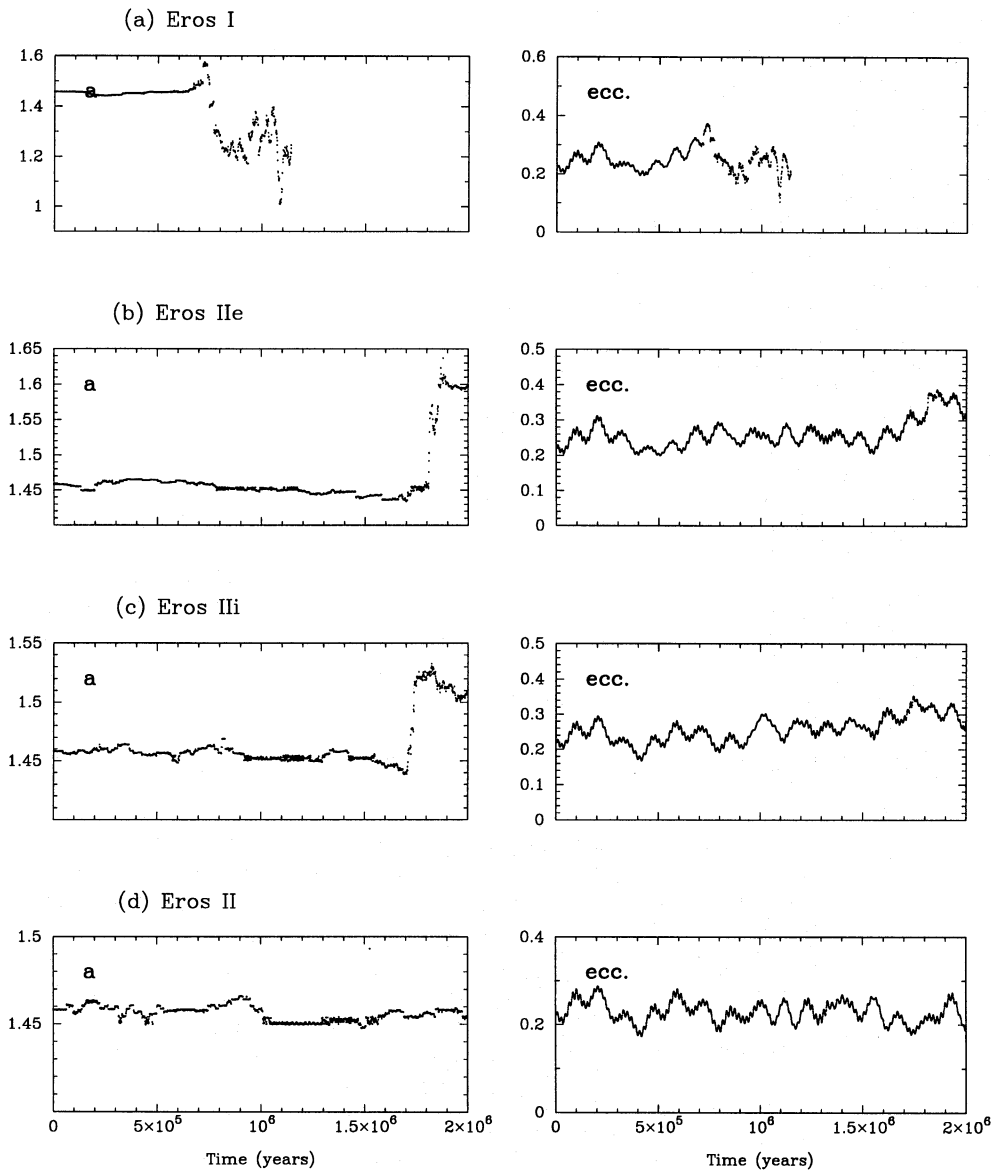


Fig. 8a–d. Evolution over 2 Myr of the semimajor axis (AU) and the eccentricity of the three Eros clones which become Earth-crossing (a–c) and of one among the five Mars-crossing clones (d).

arguments $\varpi - \varpi_V$, $\varpi - \varpi_E$, $\varpi - \varpi_M$ and $\Omega - \Omega_V$, $\Omega - \Omega_E$, $\Omega - \Omega_M$ librate temporarily around 0° with different amplitudes. Since all the orbits are dominated by CA, the effects of these resonances on the long-term dynamical evolution of the orbits are minor. However, in the case of Nereus II, when there are no strong perturbations due to CA, the evolution of the eccentricity appears to be related to the librations of the secular argument $\varpi - \varpi_M$ and the increase in inclination appears to be due to the presence of both the ν_{13} and the ν_{14} resonances (see Fig. 7). Thus, at least in some cases those resonances may play a role in the evolution of NEAs with $a < 2$ AU.

Some secular resonances with the outer planets are also at work. While in the main asteroid belt ($a > 2$ AU) the ν_5 secular resonance with Jupiter occurs at high inclinations ($i > 30^\circ$) (Williams and Faulkner 1981, Knežević et al. 1991), in our Nereus integrations this resonance shows up at inclination values $i < 10^\circ$ (Nereus Ia and Ie), confirming what had been already found by Froeschlé et al. (1995). The corresponding

effect is a secular increase of the eccentricity (see Fig. 1). Note that when ν_5 is at work, so are ν_7 and ν_8 but with different amplitudes, since the perihelion longitude precession frequencies of Jupiter, Uranus and Neptune are 4.2575, 3.0868 and 0.6726 (in $''/\text{yr}$), respectively; although it is clear that Jupiter's perturbations are much more important. Three clones are also temporarily found in the ν_6 resonance; but two of them (Nereus I and Ia) are also affected, at about the same time, by CA, so that the ν_6 secular perturbation effects are not obvious. As for Nereus II, it gets very close to but actually not inside ν_6 , and it shows long-periodic eccentricity changes having the same periodicity as the $\varpi - \varpi_S$ secular argument. The ν_{16} resonance is present in the orbital evolution of Nereus Ia and II at inclination values between 5° and 15° , causing a secular trend in this orbital element. For Nereus Ia, ν_{16} is coupled with the Kozai resonance, with ω librating around 0° . A similar coupling had already been found by Froeschlé et al. (1991) for asteroid (2335) James, but

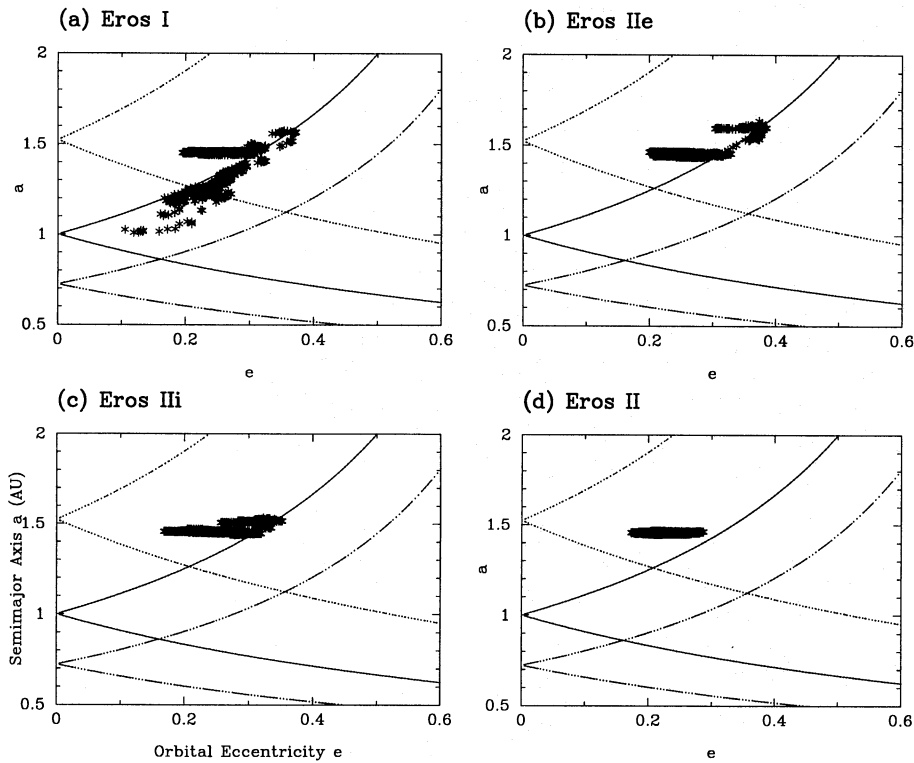


Fig. 9a–d. The same four evolutions as in Fig. 8, but in the semimajor axis (a , in AU) vs. eccentricity (e) plane over 2 Myr. Like in Fig. 2, curves corresponding to q and Q equal to the semimajor axes of Venus, the Earth and Mars are also shown.

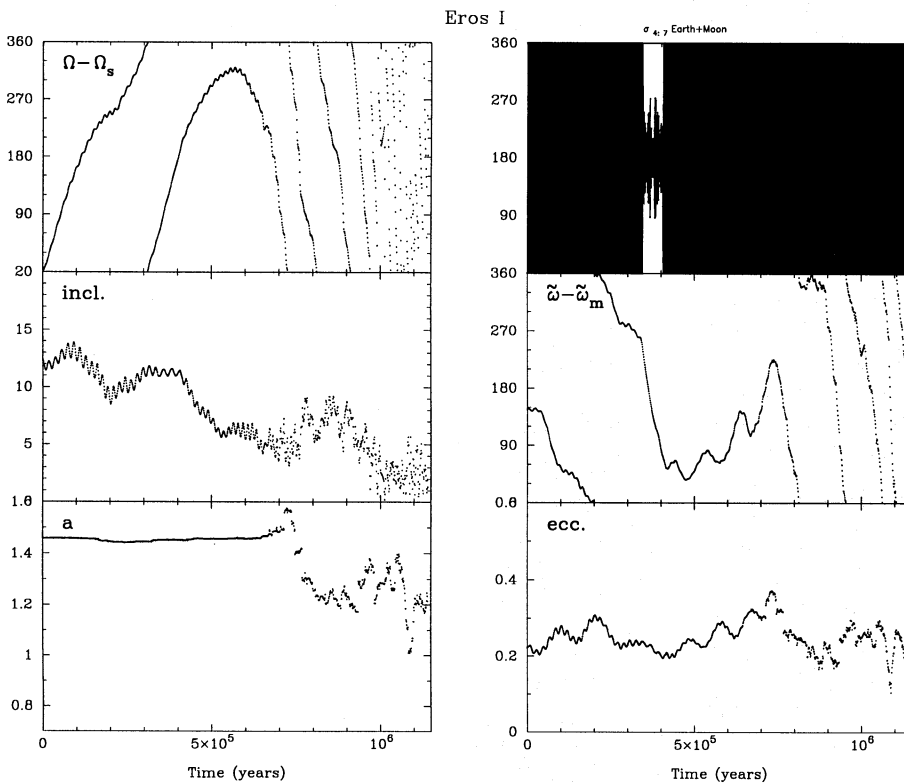


Fig. 10. Evolution of the orbital elements of Eros I until it collides with the Earth. Besides semimajor axis, eccentricity and inclination, the figure shows also three critical arguments: $\sigma_{4:7}$ of the 4/7 mean motion resonance with the Earth; $\omega - \omega_M$, $\Omega - \Omega_S$ of the ν_4 and ν_{16} secular resonances (ω_M being the perihelion longitude of Mars and Ω_S the longitude of node of Saturn).

Table 5. The same as Table 3 but for Eros and its clones.

Body	Osculating Elements	Close Approaches	Secular Resonances	Protection Mechanisms
Eros I	<i>a</i> : almost constant, then changed drastically by CA <i>e</i> : secular increase, changed by CA <i>i</i> : secular decrease, changed by CA	numerous and collision with E	$3 < t < 7.2: \nu_{16}$ $8 < t < 9: \nu_3$ $3.5 < t < 5.5: \nu_2$ $4 < t < 7: \nu_4$ $8 < t < 11: \nu_5$	4/7 (E) $3.2 < t < 4.2$
Eros II	<i>a</i> : little random-walk <i>e</i> : small regular oscillations <i>i</i> : oscillations	numerous with M	$t < 1: \nu_3$ $3.5 < t < 6: \nu_2$ $7.2 < t < 11: \nu_2$ $10.5 < t < 13: \nu_4$ $12.5 < t < 16: \nu_2, \nu_3$ $17 < t < 19.2: \nu_3$	14/13 (M) $11 < t < 13$ 4/7 (E) $13 < t < 15$
Eros Ia	<i>a</i> : changed by CA <i>e</i> : regular oscillations <i>i</i> : oscillations	numerous with M	$3.5 < t < 6: \nu_2$ $7.1 < t < 11: \nu_2$ $11 < t < 15: \nu_3$ $12.8 < t < 15: \nu_2$ $16.6 < t < 18.8: \nu_3$	
Eros Ie	<i>a</i> : changed by CA <i>e</i> : regular small oscillations <i>i</i> : oscillations	numerous with M	$0 < t < 1: \nu_3$ $3.5 < t < 6: \nu_2$ $8.2 < t < 10.8: \nu_2$ $11.8 < t < 12.7: \nu_4$ $12 < t < 15.6: \nu_3$	
Eros Ii	<i>a</i> : little random-walk <i>e</i> : regular oscillations <i>i</i> : oscillations	numerous with M	$3.5 < t < 6: \nu_2$ $7.5 < t < 11: \nu_2$ $11.2 < t < 15: \nu_3$ $16.8 < t < 19.2: \nu_3$	
Eros IIa	<i>a</i> : almost constant between CA <i>e</i> : small regular oscillations <i>i</i> : oscillations	numerous with M	$3.6 < t < 6: \nu_2$ $7.2 < t < 11: \nu_2$ $12.3 < t < 15.8: \nu_3$ $11.8 < t < 13.8: \nu_4$	5/9 (E) $14.8 < t < 17$
Eros IIE	<i>a</i> : little random-walk then fast increase due to successive CA with E <i>e</i> : oscillations and secular increase <i>i</i> : oscillations and little secular decrease	some with E	$12.3 < t < 14.5: \nu_3$ $7 < t < 15: \nu_2$ $t > 17: \nu_4$ $t > 14.2: \nu_{16}$	4/7 (E) $9 < t < 11$ $12 < t < 13$ $14.3 < t < 15.3$
Eros Iii	<i>a</i> : little random-walk then fast increase due to successive CA with E <i>e</i> : small oscillations <i>i</i> : oscillations	some with E	$3.5 < t < 5.8: \nu_2$ $7.2 < t < 15: \nu_2$ $11.9 < t < 18.5: \nu_3$ $t > 13: \nu_4$ $t > 14.8: \nu_{16}$	4/7 (E) $9 < t < 13$ $14 < t < 15.5$

at a semimajor axis > 2 AU, at a high inclination and with ω librating about 270° .

crosser one, whereas the corresponding evolutions in the (a, e) plane are represented in Fig. 9.

3.2. (433) Eros

As explained in Sect. 2, the orbits of the “nominal” (433) Eros and its three clones were integrated on two different computers, so that we have obtained eight different orbital evolutions. Milani et al. (1989) defined the Eros-class orbits as those which do not cross the Earth’s orbit, simply because their perihelion never gets smaller than 1 AU, at least during their 2×10^5 yr integration time span. Although shallow approaches with the Earth were found to occur, with minimum approach distances always exceeding 0.03 AU, the orbital elements do not show strong CA-related changes. Considering the same integration time span, our results agree with the Milani et al. definition. But on a longer time span, we actually find two classes of dynamical behaviours (see Tables 5 and 6): three clones (Eros I, IIE and Iii) become Earth-crossers within 2 Myr, and even Eros I was observed to collide with the Earth; the other five clones remain just Mars-crossers during the whole integration span, and their orbital evolution is not affected by CA with the Earth. Fig. 8 shows the evolution of the semimajor axis and eccentricity of the three objects becoming Earth-crossers and of a typical Mars-

Before discussing separately the two kinds of behaviours, we report some results on the statistics of Earth CA minimum distances which, like for Nereus, can be extrapolated to estimate Eros’ collisional lifetime with the Earth. Considering only the clone (Eros I) which always stays in the Earth-crossing region, this lifetime is found to be about 120 Myr, fairly typical for an Apollo-like orbit (Bottke et al. 1994). But if all the eight clone orbits are considered together, for an overall integration time of 16 Myr, the lifetime becomes much longer, some 1.4 Byr. The reason is clear from the f_1 values listed in Table 6, which are zero or $\ll 1$ for 7/8 Eros clones. Therefore, whereas we cannot exclude that Eros will impact the Earth within the next few Myr (like in our Eros I integration), statistically one should expect a much longer lifetime, with most of its orbital evolution occurring in the Mars-crossing (Amor-like) region. Note that according to the f_2 values listed in Table 6, it is very likely that Eros has spent at least the last few Myr with the aphelion in the main belt; therefore, when the cratering rate on its surface will be estimated from the NEAR images, a main-belt projectile population will have to be assumed to estimate its age.

Table 6. The same as Table 4 but for Eros and its clones.

Body	a_{min} (AU)	a_{max}	e_{min}	e_{max}	i_{min} (°)	i_{max}	min. dist. (AU)	f_1 (%)	f_2 (%)
Eros I	1.009	1.575	0.105	0.372	0.209	13.872	0.1384 (V) 5.979×10^{-6} (E) 7.964×10^{-4} (M)	41.16	70.49
Eros II	1.448	1.466	0.173	0.287	8.471	14.974	0.347 (V) 7.834×10^{-2} (E) 1.594×10^{-3} (M)	0	100
Eros Ia	1.465	1.515	0.187	0.298	8.857	15.734	0.354 (V) 7.720×10^{-2} (E) 4.600×10^{-4} (M)	0	100
Eros Ie	1.450	1.472	0.163	0.292	7.267	13.740	0.323 (V) 7.878×10^{-2} (E) 1.395×10^{-3} (M)	0	99.5
Eros Ii	1.455	1.473	0.183	0.294	8.717	15.617	0.354 (V) 8.079×10^{-2} (E) 1.154×10^{-3} (M)	0	100
Eros Ila	1.438	1.484	0.182	0.304	8.032	14.467	0.331 (V) 5.675×10^{-2} (E) 4.185×10^{-4} (M)	0	100
Eros IIf	1.434	1.638	0.200	0.386	5.604	14.072	0.259 (V) 1.456×10^{-3} (E) 3.797×10^{-4} (M)	9.9	100
Eros Ili	1.439	1.533	0.168	0.352	5.852	13.854	0.287 (V) 4.494×10^{-3} (E) 3.955×10^{-4} (M)	6.4	100

3.2.1. Earth-crossing orbits

The three bodies becoming Earth-crossers are under the control of the same dynamical mechanisms. However, two of them (Eros IIf and Ili) become Earth-crossers after more than 1.5 Myr, whereas Eros I gets into the Earth-crossing region after only 5.5×10^5 yr and even hits the Earth at $t = 1.14$ Myr.

During their Mars-crossing evolution, for several times the first two bodies are temporarily in the 4/7 mean motion commensurability with the Earth. Eros IIf gets locked three times in this resonance, each resonance period lasting less than 2×10^5 yr (see Table 5); Eros Ili stays temporarily twice in the resonance, for 1.5×10^5 and 4×10^5 yr. This resonance-related protection mechanism allows these bodies to lengthen their evolution in the Mars-crossing region. Moreover, their eccentricity oscillates regularly between about 0.2 and 0.3 (Fig. 8), while the oscillations of i have an amplitude less than 5° . When the first effective CA to the Earth occurs, they are located in a region where two secular resonances overlap (see Table 5), namely ν_4 ($\dot{\varpi} \approx \dot{\varpi}_M$) and ν_{16} ($\dot{\Omega} \approx \dot{\Omega}_S$). The effect of the ν_{16} resonance is to decrease secularly the inclination from about 14° to 6° for both of them. The smaller inclinations of course increases the probability of CA to the planets. Moreover, owing to the ν_4 resonance their eccentricity grows up secularly from about 0.2 to 0.38 and from 0.25 to 0.35 for Eros IIf and Ili, respectively, the short oscillation period of e being correlated with that of the critical argument $\varpi - \varpi_M$ (like in Fig. 10 for Eros I). These resonance overlapping effects lead the orbits to enter the Earth-crossing region ($q < 1$ AU), to undergo CA with minimum distances of the order of 10^{-3} AU from the Earth, and then to stay in this region until the end of the integration. As for Eros I, before the same secular mechanism starts, it is also locked temporarily in the 4/7 mean motion commensurability with the Earth. Then the oscillations of the eccentricity are well corre-

lated with those of the $\varpi - \varpi_M$ critical argument (see Fig. 10), so that e increases secularly up to about 0.33. Moreover, the inclination decreases secularly from about 12° to 4° due to ν_{16} . Therefore, the body gets well into the region strongly dominated by CA to the Earth (Fig. 9), and afterwards minimum distances of the order of 10^{-3} AU are recorded, ejecting the orbit from the resonant state. However, before colliding with the Earth, the orbit also stays inside the ν_5 resonance for about 3×10^5 years. Though the effect of this resonance is not obvious given the perturbations due to CA, it may play some role in leading the object to the subsequent collision.

Secular resonances with Venus and the Earth do also occur during the evolution of the three bodies (see Table 5), but their contribution to the changes of the elements is not apparent.

3.2.2. Mars-crossing orbits

Five Eros clones undergo many CA to Mars (see Table 5), down to minimum distances of the order of 10^{-4} AU. However, due to the small mass of the planet, no drastic change in the osculating elements is observed (Fig. 8). Moreover, two objects are temporarily locked in several mean motion resonances with the Earth or Mars (see Table 5). As a consequence, as we already noted in the case of Nereus, the semimajor axis oscillates around a constant value, corresponding to the centre of the resonance. It is remarkable that even the 13/14 mean motion resonance between Mars and Eros II provides an effective protection from close encounters during some 2×10^5 yr. The three other objects may also stay temporarily in some other mean motion resonances, of too high order to be detectable. For all the objects the minimum distances to the Earth always exceed the 0.03 AU threshold used by Milani et al. (1989) to define the Eros class (see Table 6). Note that although two bodies (Eros Ie and Ila)

stay temporarily in the ν_4 resonance, this resonance alone is not as effective as it is when it overlaps with the ν_{16} one. In summary, all these five bodies appear to evolve on a typical “slow track”, according to the terminology of Farinella et al. (1994) and Froeschlé et al. (1995).

Like for the Earth-crossing orbits described earlier, the presence of secular resonances with Venus and the Earth does not seem to play an effective role in affecting the five orbital evolutions.

4. Conclusions

In this paper, we have studied by purely numerical integrations the possible dynamical evolutions over 2 Myrs of the two NEAs (4660) Nereus and (433) Eros. These objects have a particular interest, because their morphological, physical and compositional properties should be determined in the near future by two dedicated space missions.

The main conclusions we can draw from the five integrated orbits of (4660) Nereus and its clones are:

1. All the orbits are dominated by the close approaches with the Earth, causing a random-walk like evolution of the semi-major axis. Thus, according to the definition of Milani et al. (1989), these orbits can be classified for most of the time in the so-called Geographos class.
2. However, four of the orbits get temporarily protected from CA (over time intervals of the order of 10^5 yr) by different dynamical mechanisms: (a) the Kozai resonance, which occurs here at a small inclination ($i < 10^\circ$), with ω librating around either 0° or 180° ; (b) high-order mean motion resonances with Venus and the Earth. These mechanisms somewhat lengthen the collision lifetime of Nereus with the planets, but not by a large amount.
3. Some secular resonances with both the inner and the outer planets are present, but in general they do not affect much the evolution of the orbital elements (except for one case in which significant changes in eccentricity and inclination are related to the ν_4 and the ν_{14} resonances with Mars).
4. No drastic qualitative change of the orbits is ever observed, such as leading to very high values of e and/or i , solar collisions, Jupiter encounters and ejections from the Solar System. However, the collisional lifetime of Nereus is probably of the order of 100 Myr with respect to impacts with both planets and other asteroids, and therefore we cannot exclude that such drastic orbital changes occur on a timescale $> 10^7$ yr. But if for instance Nereus comes from a comet-type orbital state, it is likely that the transition occurred a very long time ago.

The main results of our eight numerical integrations of (433) Eros and its clones can be summarized as follows. For the next 5×10^5 years, all the orbits stay in the Mars-crossing (Amor-type) region, namely they do not undergo deep Earth CA and sometimes they are temporarily protected by mean motion resonances with either the Earth or Mars. Later on, two types of evolution are possible:

- (i) Three bodies become Apollo-type Earth-crossers, mainly as a consequence of the effects of both the ν_4 and the ν_{16} secular resonances. One of them penetrates deeply in the Earth-crossing region, gets trapped in the ν_5 resonance and ends up colliding with the Earth after just over 1 Myr of evolution. However, such a catastrophic event does not appear likely *a priori*: its typical timescale is of the order of 10^8 yr for the Apollo-type Eros clone alone, and of 10^9 for all the eight clones together (including the Amor-like ones).
- (ii) Five objects follow a typical “slow-track” Mars-crossing evolution, similar to that observed by Milani et al. (1989) over a time scale a factor 10 shorter.

Therefore, from our integrations we conclude that (433) Eros has a small but non-negligible probability to become an Earth-crosser and even collide with our planet in the future. Such an impact by an object about twice as big as the K-T boundary impactor of 65 Myr ago, would generate a (possibly multi-ring) giant impact basin several hundred km across (Melosh 1989), and would result into a global climatic catastrophe.

As for the origin of Eros, our results are consistent with a “slow-track” evolution from the main asteroid belt, which would be consistent with Eros’ observed physical properties. As discussed by Menichella et al. (1996), the break-up event responsible for its origin must have been a particularly energetic and unfrequent one, possibly giving rise to an observable dynamical family.

Finally, we remark that this study has allowed us also to point out the likely effectiveness for realistic NEA orbits of some unusual dynamical mechanisms, such as long-lived horseshoe type orbits with Venus and secular resonances with inner planets. We plan to further study the occurrence of these mechanisms by both numerical and semi-analytical methods in the near future.

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