

The long term evolution of Atens and Apollos

R. Dvorak

*Türkenschanzstr. 17, A – 1180 Vienna
Institute for Astronomy, University of Vienna, Austria*

Abstract.

In this review we report on the investigations of the long term dynamics of the Near Earth Asteroids (NEAs). In the first part some theoretical results concerning the dynamical structure of the NEA belt are explained. We then present our knowledge of the long term evolution of the orbits of NEAs for time intervals up to several million years which were derived by extensive numerical integrations. An interesting point of investigation is the steady flux from the Atens to the Apollos and vice-versa which is caused primarily by close encounters with the Earth and Venus. We also report the results concerning the probability of collisions of the NEAs with these planets. Finally the possible capture of such objects into Trojan-like orbits – thus moving in a 1:1 resonance with one of the inner planets – is discussed.

Key words: Near Earth Asteroids – close encounters – collisions – captures

1. Introduction

In 1898 the asteroid 433 Eros was discovered and the orbit determination lead to the conclusion, that it approaches the Earth closer than any other asteroid known until that time (0.15 AU). Some decades later (in 1932) 1862 Apollo – the first real Earth crosser – was found; more than four decades later (in 1976) Aten – the first asteroid moving inside the Earth's orbit – was observed. Nowadays, knowing some hundreds of these objects, we distinguish three groups of NEAs:

- the Atens have semimajor axes smaller than the one of the Earth; their aphelion distance $Q = a(1 + e) > 0.983$ AU, which is equivalent to the mean perihelion distance of the Earth
- the Apollos with semimajor axes larger than the one of the Earth and a perihelion distance $q = a(1 - e) < 1.017$ AU, which corresponds to the mean aphelion distance of the Earth
- the Amors with semimajor axes larger than the one of the Earth and a perihelion distance $1.017 < q < 1.3$ AU, which means that they do not cross the Earth's orbit, but stay inside the one of Mars.

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The research on the dynamics of Near Earth Asteroids (=NEAs) got new impulses because of two events: the crash of the split comet Shoemaker-Levy 9 on Jupiter and the finding of the crater of a 10 km asteroid in Yucatan; the collision with the Earth took place about 65 million years ago and caused the death of most of the species. Thus more and more astronomers are interested in this subject and the public opinion is in favor for financing the investigation of the dynamics of these asteroids. The Spaceguard Foundation, which is hosted by the Istituto di Astrofisica Spaziale of the Italian National Research Council in Frascati (Rome), plays an important rôle in the coordination of these activities. Several different groups are doing observations of the NEAs (like the Spacewatch, NEAT, LINEAR, BAO Asteroid Program, O.D.A.S etc.) but the major work of efficient collection and orbit determination is done by the Minor Planet Center operated by the Smithsonian Astrophysical Observatory.

From early work of Shoemaker *et al.* (1979) and Wetherhill (1989) it was clear that these objects are rather important for the geological history of the Earth. A witness for the collisions of such bodies is our Moon and also Mercury, who both have surfaces full of craters. The first estimates of such events in connection with the lifetimes of the NEAs are in rather good agreement with recent numerical and theoretical work.

In the first part of this review of long term dynamics of the NEAs some theoretical results concerning the dynamical structure of the NEA belt will be explained. Then we present the long term dynamical evolution of the NEAs for time scales of several millions of years. After the discussion of the probabilities of encounters of such objects with the inner planets we finally show the results of captures of such objects into Trojan-like orbits by Venus, Earth and Mars.

2. Theoretical considerations

The dynamical evolution of the orbits of small bodies in the Solar system shows roughly speaking 2 different patterns: one is very irregular and chaotic looking where repeated encounters with planets take place. The other one is governed also by close approaches to the planets but the orbit looks very often like a step function when we plot just the semimajor axes (Fig. 1). As an example we show the orbits of (3354) Amun (step – function like orbit) and (2340) Hathor (highly chaotic development) for 5×10^5 years.

When we check the semimajor axes in the phases when they are constant, it is obvious, that they move in a resonance. During this period of time, which can be rather long and can last several hundred thousand years, sometimes the eccentricities and inclinations undergo oscillations such that the quantity $\sqrt{1 - e^2} \cos i$ is constant. This behavior is quite well visible in Fig. 2, where we plotted for Amun the eccentricity and the inclination (in fact $\sin i$) for 5×10^5 years. The coupled oscillations between eccentricity and inclination is visible in

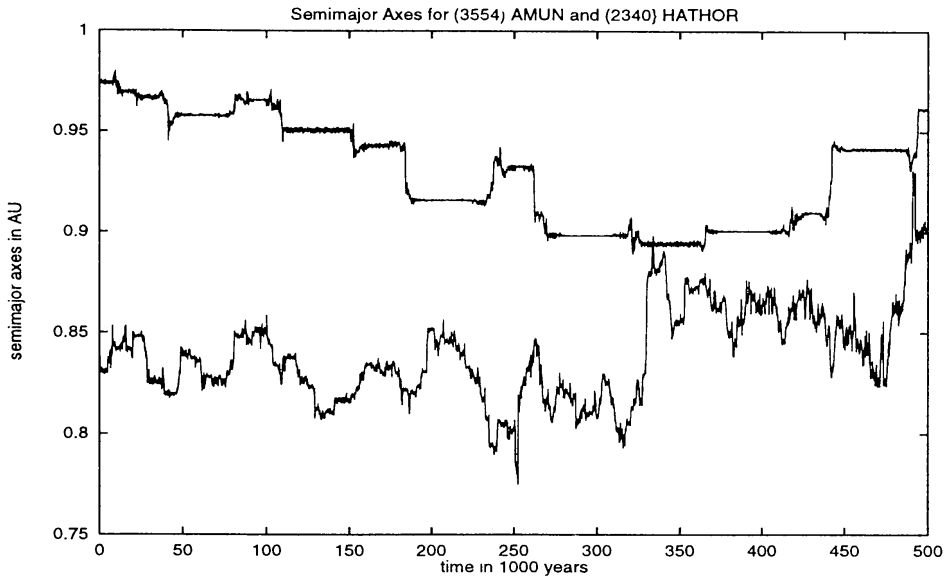


Figure 1. Semimajor axes for Amun and Hathor for 5×10^5 years

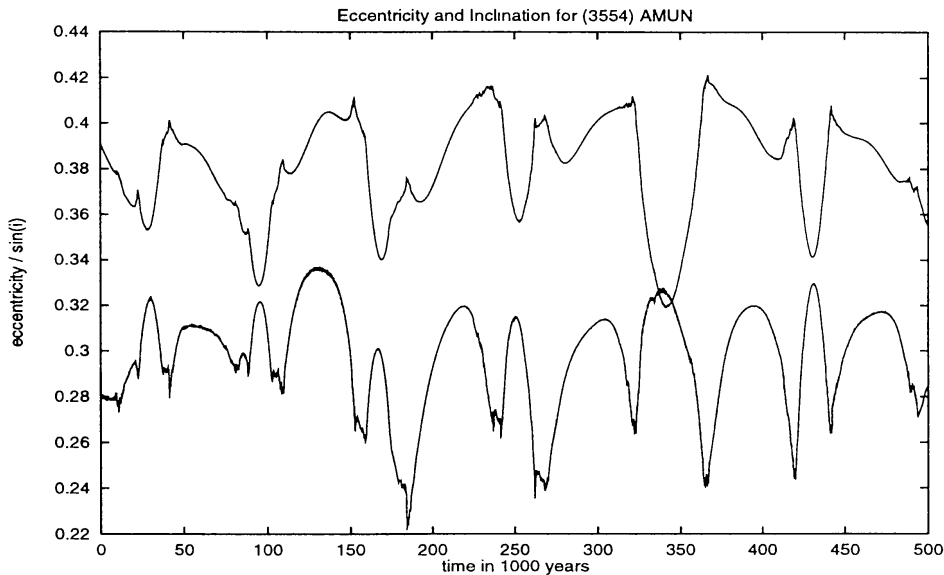


Figure 2. Eccentricity (lower line) and inclination ($\sin i$, upper line) of Amun for 5×10^5 years

many of the figures of the dynamical evolution of the orbital elements of the Atens and also of the Apollos.

Kozai (1962) used the corresponding integral of motion $H = a\sqrt{1 - e^2} \cos i$ (which is identical with the well known Delaunay variable H) to develop his theory leading to the conclusions that there exist a new kind of resonances known as the Kozai resonance:

- when the precession rate of the longitude of the perihelion of a body in the Solar system is equal to the precession rate of its nodal longitude then the precession of the argument of the perihelion stops ($\dot{\omega} \approx 0$)

In the original paper it was found, that taking into account only Jupiter as a perturbing planet, highly inclined orbits may suffer from an increase of the orbital eccentricity. In a recent paper Thomas and Morbidelli (1996) extended the theory such that they included the perturbations of all giant planets. This theory was applied to objects with semimajor axes $a < 2$ AU by Michel and Thomas (1996) and compared to numerical results. New results by Gronchi and Milani (1998) showed that “for every value of the asteroid/comet semimajor axis, and for an arbitrary number of perturbing planets, there is a stable region of orbits free from node crossings; it corresponds to either circulation or libration of the argument of perihelion.”

The perturbations caused by secular resonances are known to act as well on the main belt asteroids as on other asteroids with orbits outside of Jupiter or inside Mars. Secular resonances occur when the precession of the node or the perihelion of an asteroid is in resonance with the nodal or perihelion precession rate of a planet. Michel *et al.* (1996a, 1996b) and Michel (1997) investigated semi-analytically and numerically the influence of the secular resonances on orbits for semi major axes $a < 2$ AU and located them in an inclination versus semi major axes diagram for a fixed value of the eccentricity ($e = 0.1$).

According to their results the secular resonances are acting for asteroids with semimajor axes $0.4 < a < 0.65$ and $0.82 < a < 0.9$ and outside the orbit of the Earth for asteroids $1.2 < a < 1.4$ and $1.7 < a < 2.0$ whereas the Kozai mechanism is acting for asteroids with $0.65 < a < 0.82$ and $0.9 < a < 1.1$ (units are in AU). But we should emphasize that the region of all these resonances depend also on the eccentricity. Thus not only the close encounters with the inner planets but also the secular resonances can change the orbit of an asteroid moving in the regions given above.

3. Long term evolution

The dynamical evolution of the Near Earth Objects was first studied with the aid of numerical integrations in the mid eighties by Rickman (1985), Hahn and Rickman (1985) and Hahn and Lagerkvist (1989). In the last mentioned investigation the orbits of 25 selected asteroids were integrated up to 10^5 years using a dynamical model where all the planets with the exception of Mercury were included. There it was pointed out, that even for Aten-Apollo-Amor objects the mean motion resonances with Jupiter play an important rôle, a fact, which also has been found in recent studies (e.g. Michel, 1997). A major step forward in understanding the dynamics of the NEAs was accomplished by Milani *et al.* (1989) where several hundred Earth crossing asteroids were integrated for 2×10^5 years. There a new classification was proposed to replace the distinction

between Atens – Apollos – Amors because in the classical groups the dynamical similarities of these asteroids is not taken into account.

Further it is evident that there is a steady exchange of asteroids between these classes caused by close approaches (also Michel, 1997). These results were recently confirmed in a numerical study by Dvorak and Pilat-Lohinger (1999 = paper II). In this latter research the orbits of the NEAs were integrated numerically for 1 million years; the mixing between Apollos and Atens was investigated as well as the encounters with the Earth computed. In another earlier paper (Dvorak 1998 = paper I) the encounters of the Atens with the Earth and with Venus were investigated.

When we believe that the total number of Atens is ~ 100 and of Apollos it is ~ 500 (after estimations by Helin and Shoemaker (1979)) we already know 30 percent of these groups. The number of actually observed asteroids is rapidly growing::

- Atens in 1979 (3), 1984 (4) , 1994 (17) and 1998 (24)
- Apollos in 1979 (23), 1984 (34) , 1994 (152) and 1998 (218).

This fact is due to the interest in these objects, the better instrumentation techniques which open even for amateurs very good possibilities of observations (CCDs) and the already mentioned groups of investigators with special telescopes dedicated to observe such Earth approaching objects. In Fig. 3 we show the initial eccentricities (inclinations) versus the semimajor axes for a part of asteroids with well established orbital elements. No major differences in the initial conditions – apart from the semimajor axes – are visible: the Atens posses slightly smaller eccentricities than the Apollos; the inclinations of the Atens are as well slightly smaller than for the Apollos.

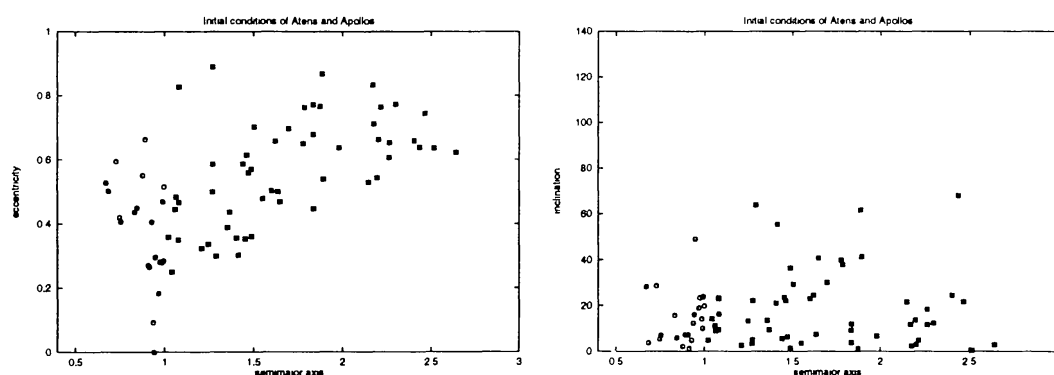


Figure 3. The initial elements of the Atens (open circles) and the Apollos (full squares): eccentricities versus semimajor axes (left graph) and inclinations versus semimajor axes (right graph)

3.1. The mixing of the Atens and Apollos

It is obvious from earlier work and the results of paper II that the objects of the two groups may change their “membership” during their dynamical evolution several times. Fig. 4 shows the result of the Atens and only one part of the Apollos (54) for which the orbits are well determined.

Five Atens (2062, 3362, 3753, 5590, and 45590) became Apollos and vice versa three Apollos (2063, 4460 and 4581) became Atens; in each case one Aten (1994 TF) and one Apollo (4034) developed for a short time to a member of the other group.

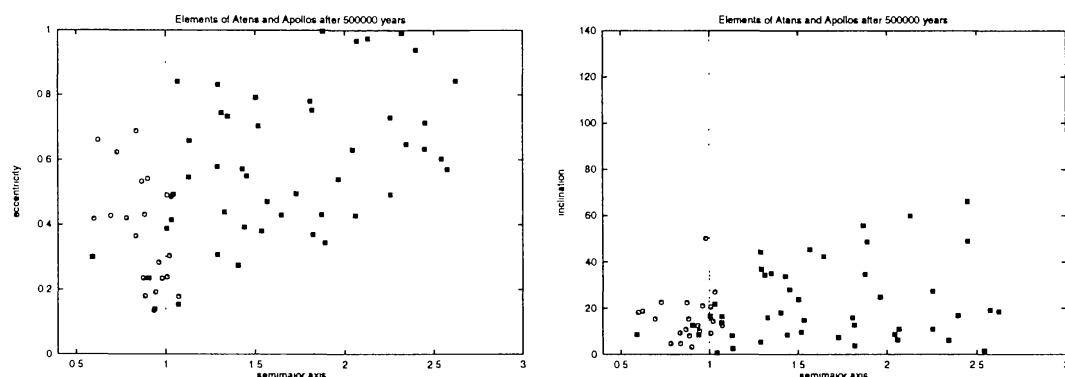


Figure 4. Eccentricities (left graph) and inclinations (right graph) versus the semi-major axes of the Atens (open circles) and the Apollos (full squares) after 5×10^5 years; the straight line for $a = 1$ is the border between Apollos and Atens

According to these results the number of Atens is dynamically in a steady state. Consequently there is no net flux from Atens to Apollos or vice-versa. Because the dynamical lifetime of an asteroid is limited due to collisions with planets, the Sun and also among themselves some sort of a “creation procedure” of new NEAs should exist. We also have a similar problem – even more difficult to solve – for the short periodic comets (Rickman and Froeschlé, 1988).

To get a more conclusive answer one has to check longer time intervals with a large number of fictitious objects which then will provide statistically more significant results.

3.2. A first example of a long term evolution orbit: Eros

In Michel *et al.* (1996, 1998) Eros’ orbit was integrated together with several “clones” for millions of years and their results coincide quite well with the ones by Milani *et al.* (1989) for the first 2×10^5 years. Their results (Michel *et al.*) can be summarized as follows:

Within half a million years all the integrated orbits stayed to be Amors but then 2 groups developed: 5 out of the 8 clones became Apollos suffering from many close approaches and even collisions with the Earth and 3 of them continued to be Amors over 16 million years. From the point of view of its

dynamical evolution the results are consistent with the slow-track theory which says that secular resonances brought Eros from the main belt to the Earth. The authors conclude that Eros type orbits may have collisional life times (with Earth or Mars) of about 10^9 years whereas the dynamical lifetime is an order of magnitude lower (50 to 100 million years). This is why they point out that Eros has only a small chance of eventually hitting the Earth.

According to the results of my own numerical integration – scheduled for 50 million years of dynamical evolution – Eros had no major close approaches to the Earth at the beginning, but the secular resonances acting led to a small increase in the eccentricity. Finally Eros was brought into an Earth crossing orbit (Apollo) suffering from many close approaches after about 8 million years (Figs. 5 and 6). A steady increase in the eccentricity up to 0.8 brought it into an orbit crossing all the inner planets and after an increase of its eccentricity to almost $e = 1$ Eros became a sun-grazer and thus ended its dynamical-life after 2×10^7 .

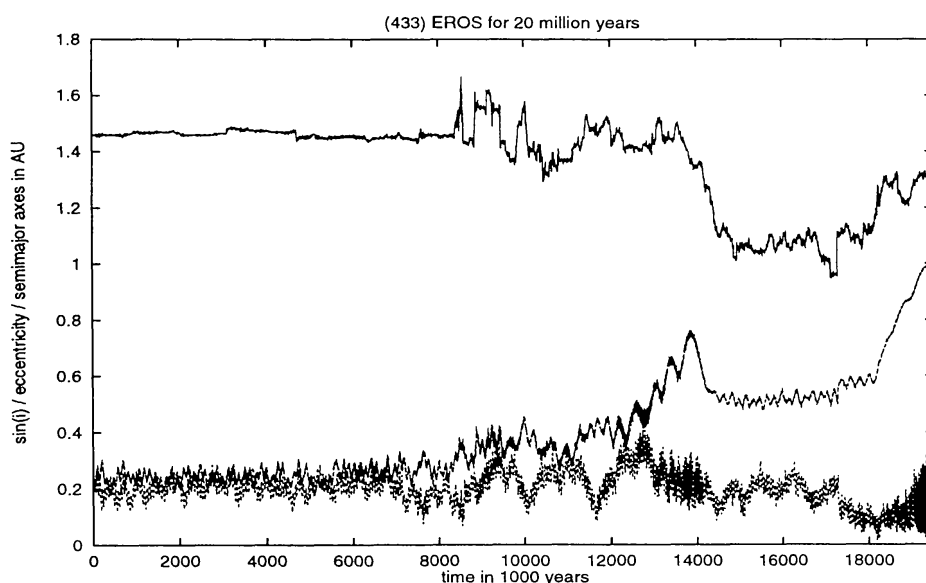


Figure 5. Elements for EROS for 20 million years: semimajor axes (upper solid line), eccentricity (dotted line) and inclination (dashed line)

It is thus evident that asteroids may “finish” their lives in the Solar System due to different processes: after a close approach to Jupiter (or another major planet) they can be ejected; they can suffer from collisions with another asteroid and break into different smaller pieces. It is also possible that they hit the Sun when they have achieved very high eccentric orbits and they may even collide with a planet (e.g. the Earth, which then can have catastrophic consequences for the biosphere).

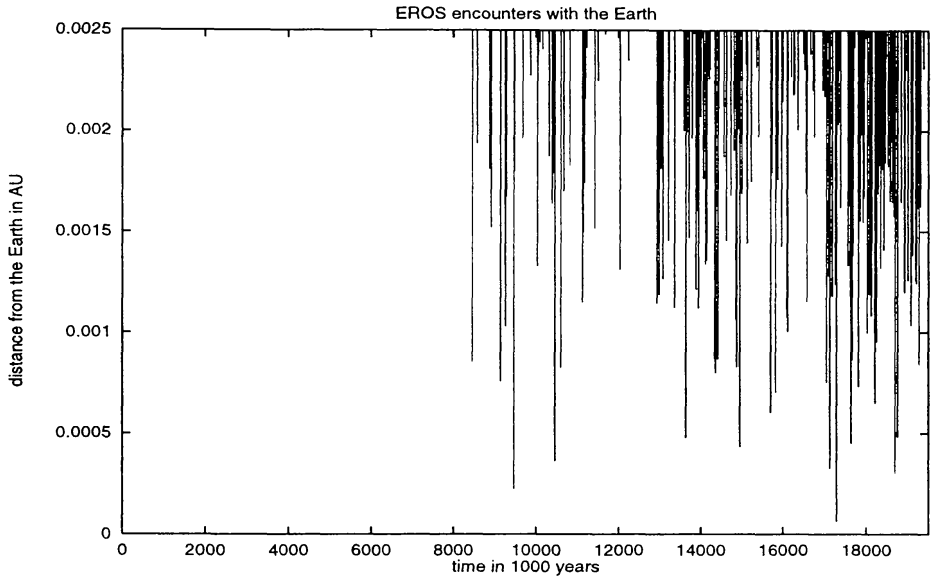


Figure 6. EROS encounters with the Earth within the next 20 million years

4. Encounters and collision probabilities

I a series of papers Steel and others (e.g. Steel and Baggaley, 1985; Steel, 1995) computed the probabilities of impact on the Earth with statistical methods. They made a distinction between small objects with a limiting magnitude $H_{lim} \sim 18.0$ producing craters on the Earth with an estimated diameter of $d < 10$ km – according to their own size of about 1 km in diameter – and larger objects producing global catastrophes. Table 1 shows the respective results derived by the authors mentioned above. In addition to the computed probabilities (P_c) the computed collision velocities are given and the new numerically determined values of P_c are shown.

Table 1. Mean Earth-collision probabilities (P_c) and speeds (v_c) for different classes of objects (after Steel, 1995) compared to the new numerical P_c

Class	Number	P_c ($\times 10^{-9} yr^{-1}$)	v_c (kms^{-1})	P_c (num)
$H < 17.7$	88	4.53	18.4	
$H < 18.0$	99	4.89	18.0	
Apollos	152	9.33	15.7	8.2
Atens	17	24.30	15.1	38.6
Apollos + Atens	169	10.83	15.5	16.7
all $e < 0.2$	11	23.36	13.7	
all $e > 0.2$	158	9.96	15.8	

Rabinowitz (1994, 1997) computed also the size distribution of the NEOs between 10 m and 10 km using extensive Monte Carlo simulations and concluded

that the larger bodies may come from the main belt via secular perturbations, whereas smaller bodies may have also other sources when the size distribution – as it is after the observations – is inspected. He also found that using his statistical model there should exist a major concentration of Amors having semimajor axes $2.0 < a < 2.6$ AU and another one for $1.3 < a < 1.5$ AU ; these results are confirmed by the Spacewatch observations for smaller objects.

In paper II the close approaches to the Earth for the Atens and Apollos are computed and they are compared to other estimations. The respective results are shown in Fig. 7 where we plot the Aten and the Apollo encounters over the time interval of 1 million years. We counted the number of approaches to the Earth within 0.01 AU for all integrated orbits and normalized them; it is immediately seen from the plots that the encounters of the Atens are approximately 3 times more frequent than for the Apollos which is easily understood from the different mean orbital periods of Apollos and Atens ($\langle P_{Apollos} \rangle / \langle P_{Atens} \rangle \sim 2.6$). As a consequence an average Aten may encounter the Earth three times while an Apollo just crosses the Earth orbit once (ignoring that the Apollos orbit are more inclined than the ones of the Atens).

It is obvious from Tab. 1 that the quantities found by a statistical approach and by a numerical one are not very different. The encounter velocities given in this table can also be estimated by a simple calculation: the Apollos, being close to their perihelia have a velocity close to 36 km s^{-1} , the Atens being close to their aphelia, move only with 18 km s^{-1} (compared to the Earth's approximate velocity of 30 km s^{-1}).

In another investigation the close encounters of minor bodies with the Earth and Venus (Carusi and Dotto, 1996) for five different groups of objects (Apollos, Atens, Amors, short-periodic comets and long-periodic comets) were computed. Statistical results were derived using short time numerical integrations; these results agree quite well with the ones of our paper I where we concluded that an Aten will come to Earth as close as the Moon every 50 000 years, whereas such Venus encounters occur approximately every 40 000 years. Additionally in their integrations (Carusi and Dotto, 1996) Earth encounters within 0.1 AU for an Aten occur 0.0719 per year and for an Apollo 0.0216 per year; the ratio of ~ 3 for the frequency Aten/Apollo encounters fits quite well to other results.

Summarizing the results of paper II we come to the following numbers: for encounters within the Earth – Moon distance we get for the 54 Apollos 386 encounters compared to 431 encounters for the 21 Atens found in paper I. Thus encounters with the Earth within the distance Earth – Moon happen with a mean time interval of 140 000 years for an Apollo compared to 50 000 years for an Aten (again the ratio is close to 3).

Fig. 8 is a compilation of the results of the encounters of the NEAs over different time scales (1000 years, 100 000 years and 1 million years) and different minimum distances (10 times the Moon's distance, the Moon's distance and 1/10 of the Moon's distance). On Fig. 8a the star on the left side shows the next close encounter of 4179 Toutatis in September 2004 (distance = 0.0104 AU). No real

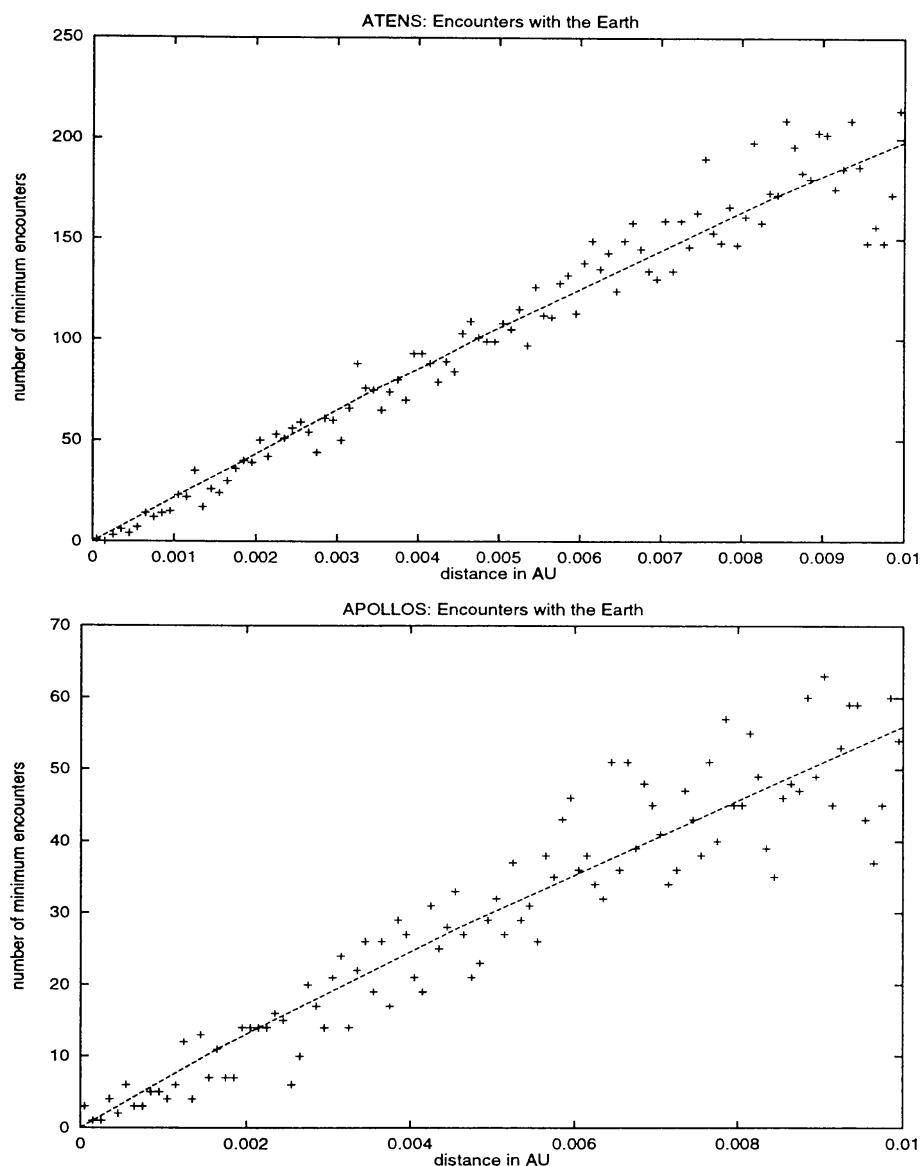


Figure 7. Aten (upper graph) and Apollo encounters (lower graph); x-axis closest encounters during one approach to the Earth, y-axis number of encounters normalized to 1 billion year

close encounter for this sample of NEAs can be expected for the next 1000 years. Fig. 8b shows how many of these asteroids come close to the Earth during the next 100 000 years. The closest one still passes some 70 000 km from the Earth in about 80 000 years. Fig. 8c shows the encounters within 1/10 of the Moon's distance during the next 1 million years; one asteroid (1990 BG about 7×10^5 years into the future) could come as close as 9000 km. We emphasize again that the Earth – Moon system was integrated as one body and thus the rôle of the Moon is neglected. Another important remark is that all these NEAs are on highly chaotic orbits which means that are very sensitive with respect to their

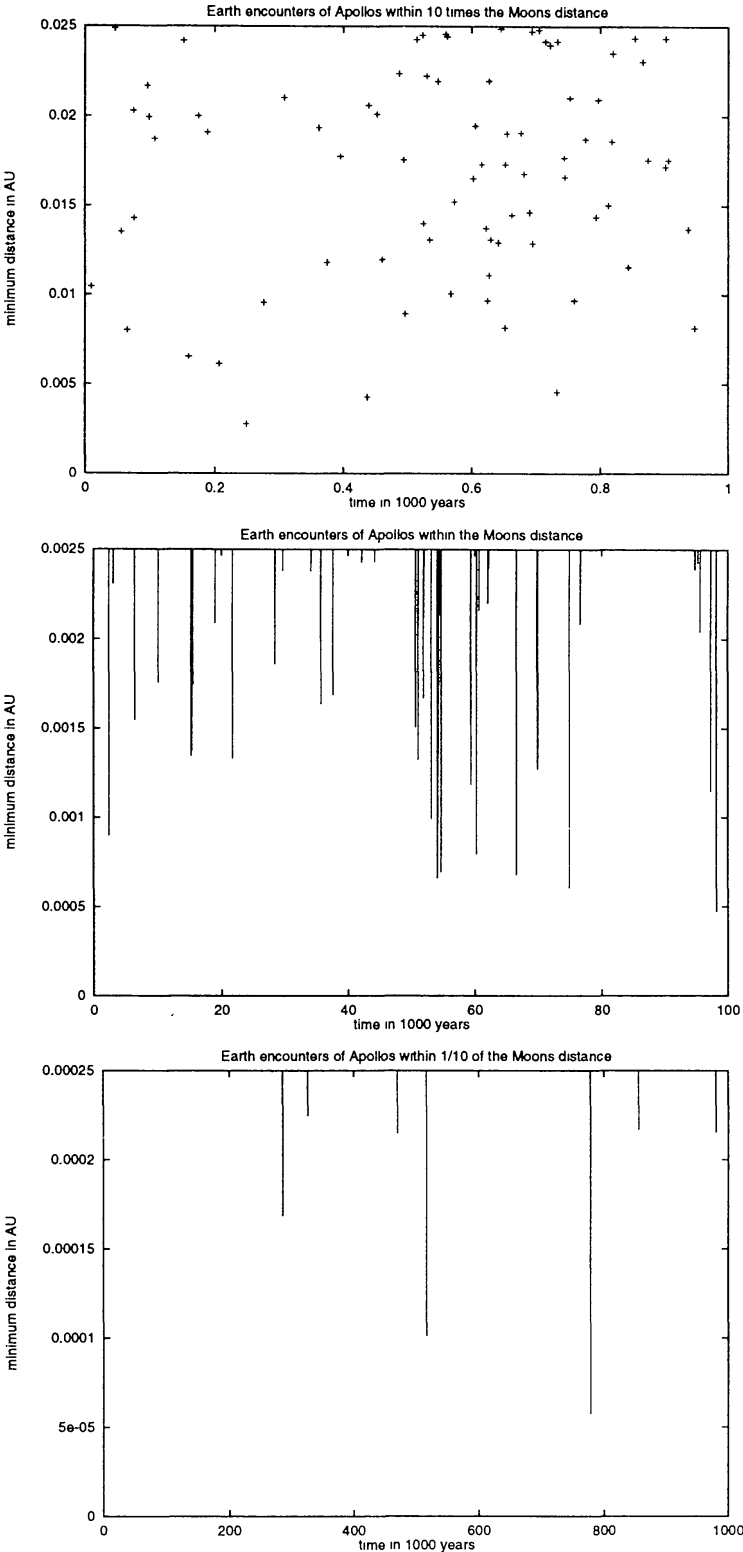


Figure 8. Earth encounters of the Apollos during 1 million years: within 10 times the Moon’s distance (upper graph), within the Moon’s distance (middle graph) and within 1/10 of the Moon’s distance

initial conditions and thus depend strongly on the model used. Therefore the above results are only of statistical character, because not one single orbit is accurate for longer than some 100 to 1000 years (few approaches to a planet).

5. Capture into the 1:1 resonance

One interesting feature for an orbit of a NEA is that there may happen captures into the 1:1 resonance with the planets Mars, Earth and Venus. Some examples are shown in Fig. 9 where one can see captures occur for all inner planets (Mercury was not taken into account in this integration).

- (5011) Ptah is captured twice to be a Mars Trojan for some 150 thousand years during 1 million years (Fig. 9a: solid line). The eccentricity changes regularly between 0.45 and 0.5 (Fig. 9b: solid line) and also the inclination shows only small variations between 6° and 12° (Fig. 9c: solid line).
- (33591) becomes a Venus Trojan after more than 900 thousand years. Before the capture it shows an interesting pattern of repeated close encounters with the Earth for approximately 200 thousand years, which brings it finally close to Venus (Fig. 9a: dashed line). The eccentricity also shows a similar pattern in between the close encounters with the Earth up to the moment when it is captured by Venus (Fig. 9b: dashed line); the inclination stays always smaller than 10° (Fig. 9c: dashed line)
- (34093) is always close to the Earth but after some 250 thousand years possesses exactly the same semimajor axis as the Earth for about 100 thousand years (Fig. 9a: dotted line). Before and after (34093) seems to be in the Kozai resonance according to the opposite behavior of the eccentricity ($0.15 < e < 0.85$) and the inclination ($30^\circ < i < 65^\circ$) (Fig. 9b and 9c: dotted line).

A respective check of the relative positions showed that these captures are not satellite captures. Such captures also may occur and are especially reported for comets captured temporarily by Jupiter as quasi satellites. Recently one of these captures was also observed: The object 1991 VG, which was discovered by the Spacewatch telescope, shows repeatedly short captures by the Earth (Tancredi, 1998).

5.1. A second example of a long term evolution: Nereus

In a paper by Michel *et al.* (1966b) Nereus' orbit and some neighboring orbits (they call them clones) were integrated for 2 million years. Globally they found that in the Nereus' regime all orbits are dominated by close approaches to Venus, Earth and also to Mars which lead to a random walk in phase space. Sometimes they are temporarily captured into the Kozai resonance and also

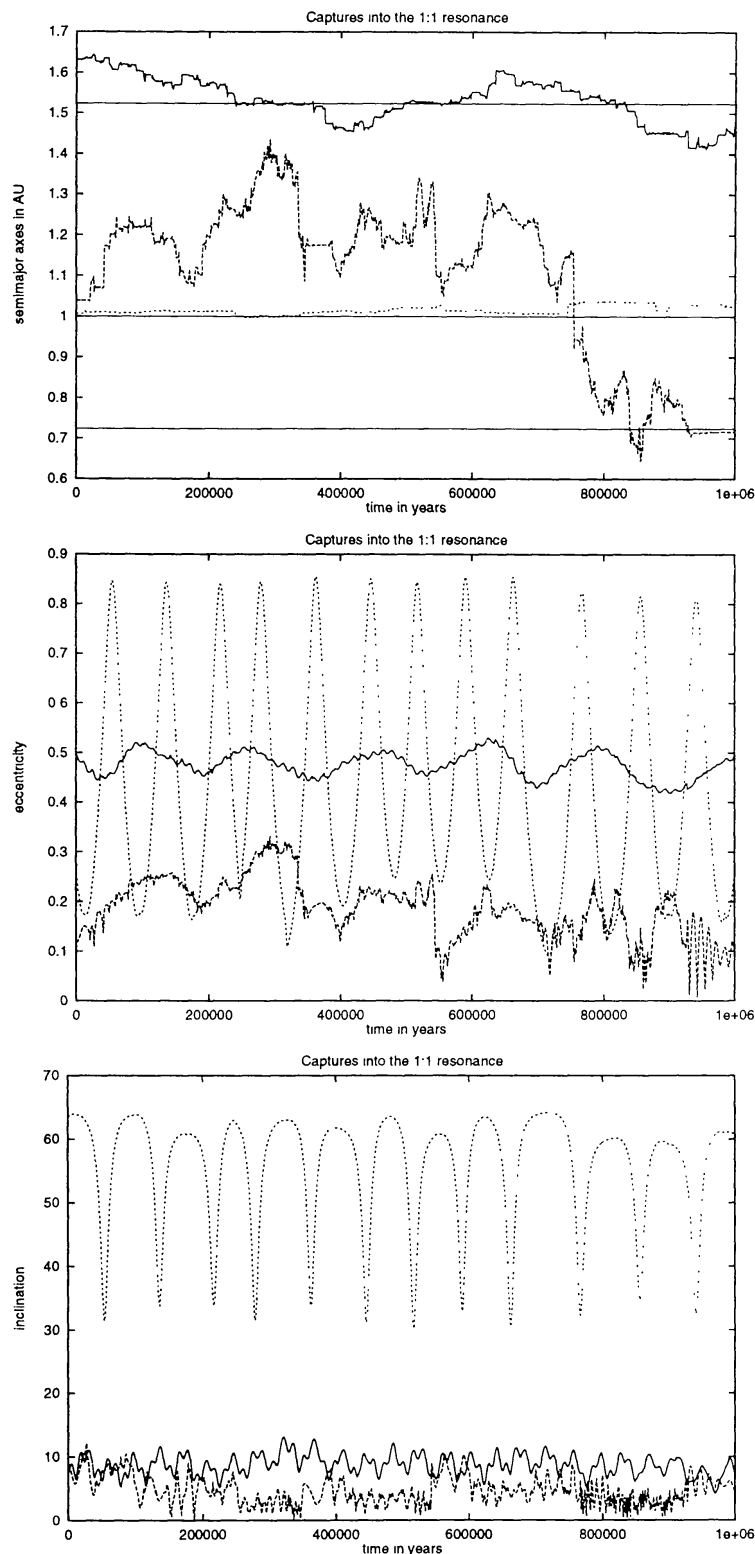


Figure 9. Semimajor axes (upper graph), eccentricities (middle graph) and inclinations (lower graph) for Ptah (solid line), 33591 (dashed line) and 34093 (dotted line) for 1 million years

into high order mean motion resonances with the Earth and Venus. For none of these fictitious bodies (Nereus + 4 clones) a collision with the Sun, or a close approach to Jupiter leading to a subsequent escape from the Solar system was observed. These results led the authors to the conclusion that the average collision lifetime is in the order of 10^8 , years which coincides quite well with the above given results for the collision probabilities.

Additionally they found that one of their fictitious asteroids was captured by the Earth into a Trojan like orbit and another one into a “Trojan” of Venus, which shows in fact a horselike orbit with respect to Venus. In our results we found for Nereus and neighboring “clones” a capture into a Mars Trojan. Thus it seems that the region where Nereus moves is one where such captures by the 3 inner planets are very probable.

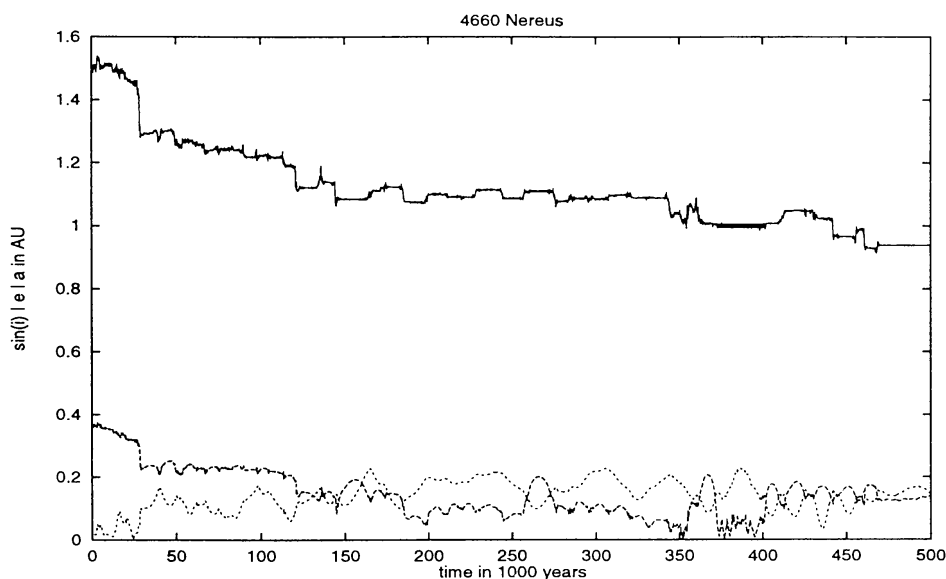


Figure 10. The orbital elements Nereus for $5 \cdot 10^5$ years; semimajor axes (solid line), eccentricity (hatched line) and $\sin i$ (dotted line)

Nereus' semimajor axis is gradually diminishing after a first close encounter with the Earth after 30 000 years (Fig. 10). From 370 000 years on Nereus seems to be captured exactly in the 1:1 resonance with the Earth for about 50 000 years – it is a Trojan of the Earth. After that the Kozai phenomenon is well visible from the plots where one can observe the inverse behavior for the inclination and eccentricity. This very interesting capture into a Trojan of the Earth quite often happened also for other Atens and Apollos during the integration of the orbits; it will be discussed separately after a more detailed investigation which is in progress (Dvorak and Lohinger, in preparation).

6. Conclusions

From the long term integrations which have been undertaken during the last years by different groups we clearly can see that every NEA has its own history; one could even say that each of these celestial bodies coming close to the Earth possesses its own destiny. Their dynamical lifetimes are governed primarily by four different processes:

- close approaches to the planets
- secular resonances
- mean motion resonances with the planets
- Kozai resonance

When we follow up their dynamical evolution for several million years we can – roughly speaking – distinguish two different patterns: a random walk like evolution of the semimajor axes caused by many close approaches to the planets and a step like function, where captures into mean motion resonances for up to 10^6 years can be observed. The dynamical lifetime is limited between some 10^6 to 10^9 years depending on the individual object. The destruction can be caused by collision with the Sun, when the eccentricity achieves values close to $e = 1$, or by collision with a planet. The collisions with another asteroid in the main belt is also a possible evolution, but we did not discuss it in this study. During all these long term integration no escapes from the Solar system were observed due to encounters with the inner planets; this may demand a more massive body like Jupiter.

The collision probabilities with the planets are in the order of 10–40 per 10^9 years for a single object. Furthermore the mixing of the different groups is evident from the different plots. Thus to be able to keep the number of the three groups more or less constant we need a flux of new objects (from the main belt or/and the Edgeworth–Kuiper belt) which is effective for time scales up to the age of the Planetary system.

To have better results we need very long term integrations (some 10^8 to 10^9 years) for fictitious objects of all the three groups. Finally it should again be said that any dynamical model used up to now is not complete: the rôle of the Moon for Earth encounters and Earth collisions has not yet been investigated up to now. One should also keep in mind that all the results here are only valid in a statistical sense and that they are precise for single objects up to some close encounters into the future (or the past) for several hundreds to thousand years (depending on the encounter frequency).

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References

- Dvorak, R.: 1998, *Celest. Mech. Dyn. Astron.* **69**, 103
- Dvorak, R., Pilat-Lohinger, E.: 1999, *Planet. Space Sci.* **47**, 665
- Carusi, A., Dotto, E.: 1996, *Icarus* **124**, 392
- Gronchi, G.F., Milani, A.: 1999, *Astron. Astrophys.* **341**, 928
- Hahn, G., Rickman, H.: 1985, *Icarus* **61**, 417
- Hahn, G., Lagerkvist, C.-I.: 1988, *Celest. Mech.* **43**, 285
- Hanslmeier, A., Dvorak, R.: 1984, *Astron. Astrophys.* **132**, 203
- Helin, E.F., Shoemaker, E.M.: 1979, *Icarus* **40**, 321
- Kozai, Y.: 1962, *Astron. J.* **67**, 591
- Michel, P.: 1997 *Evolution dynamique des asteroides qui croisent l'orbite de la terre*, Thèse de l'Université de Nice - Sophia Antipolis, 249
- Michel, P., Thomas, F.: 1996, *Astron. Astrophys.* **307**, 310
- Michel, P., Froeschlé, Ch.: 1997, *Icarus* **128**, 230
- Michel, P., Froeschlé, Ch., Farinella, P.: 1996a, *Earth, Moon, Planets* **72**, 151
- Michel, P., Froeschlé, Ch., Farinella, P.: 1996b, *Astron. Astrophys.* **313**, 993
- Michel, P., Farinella, P., Froeschlé, Ch.: 1998, *Astron. J.* **116**, 2023
- Milani, A., Carpino, M., Hahn, G., Nobili, A.M.: 1989, *Icarus* **78**, 212
- Rabinowitz, D.L.: 1994, *Icarus* **111**, 364
- Rabinowitz, D.L.: 1997, *Icarus* **130**, 287
- Rickman, H.: 1985, in *Dynamics of Comets; their origin and evolution*, *Proc. IAU Coll. 83*, eds.: A. Carusi and G.B. Valsecchi, Reidel, Dordrecht, 149
- Rickman, H., Froeschlé, C.: 1988, *Celest. Mech.* **43**, 243
- Shoemaker, E.M., Williams, J.G., Helin, E.F., Wolfe, R.F.: 1979, in *Asteroids*, ed.: T. Gehrels, Univ. Arizona Press, Tucson, 253
- Steel, D.I., Baggaley, W.J.: 1985, *Mon. Not. R. Astron. Soc.* **212**, 817
- Steel, D.I.: 1995, *Mon. Not. R. Astron. Soc.* **273**, 1091
- Tancredi, G.: 1998, *Celest. Mech. Dyn. Astron.* **69**, 119
- Thomas, F., Morbidelli, A.: 1996, *Celest. Mech. Dyn. Astron.* **64**, 209
- Wetherhill, G.W.: 1989, *Meteoritics* **24**, 15