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Dynamic evolution scale of NEA population: dependence on the initial orbital parameters

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Abstract. The history of crater formation on the Moon idicates that the number of NEAs larger than 50 m practically did not change over the past 2–3 Gyr. On the other hand a dynamic scale of the NEA population, which could be characterized by the depletion time by half t_{NEA}, is many orders of magnitude shorter. There are significant variations of t_{NEA} estimates by other authors. It is important to know this value more precisely, since this knowledge imposes restrictions on the mechanisms of replenishment of the NEAs, the lifetime of the Main Asteroid Belt, etc. In the Zolotarev & Shustov (2021) we have estimated t_{NEA} as 3.5 million years. We noted either that t_{NEA} for subgroups of NEAs depends on the initial orbital parameters of the subgroups. In the current study we considered this dependence quantitively. We have integrated orbits of 10 000 asteroids larger than 1 km and $q < 1.72$ AU over 20 Myr. These sample essentially includes all large NEAs (> 1 km). The NEA subsample is considered to be complete. We made integrations with the REBOUND software package using the MERCURIUS hybrid scheme (Rein et al. (2019)). To reveal dependence of t_{NEA} on orbital parameters $t_{NEA}(a, e, i)$ we divided the NEA subsample into 18 subgroups according to their orbital parameters. We found that t_{NEA} is substantially higher for subgroups with higher i and e. There is strong dependence of t_{NEA} on a. All these dependencies are explained by a different number of close approaches of asteroids from NEA subgroups to planets. We found that depletion of total NEO population can be approximated remarkably well with the following expression: $N(t)/N_0 = exp(-0.5 \times t^{0.33})$ where N_0 is an initial number and $N(t)$ – a current number of NEAs.

Keywords. asteroids, NEA

1. Introduction

Studies of dynamic properties of NEA popuation is of particular importance in the context of the problems of asteroid-comet hazard and asteroid resources. One of the most intriguing features of the evolution is that the number of NEAs remained almost unchanged over the past 2–3 billion years, although the dynamic scale of the existence of the current population is relatively short. The number of NEAs in previous epochs can be judged only by analyzing the change in the rate of impact crater formation on surfaces of non-atmospheric bodies of the Solar System. The Moon seems to be most convenient natural "log" for studying records of collisions over a long time interval (billions of years). The absence of atmosphere, water, and tectonic activity contributes to the preservation of this log. The history of the bombardment of the Moon can be described by the formula from Neukum & Ivanov (2002),

$$N(1) = 5.44 \cdot 10^{-14}(\exp(6.93t)\ 1)\ +\ 8.38 \cdot 10^{-4}t, \qquad (1)$$

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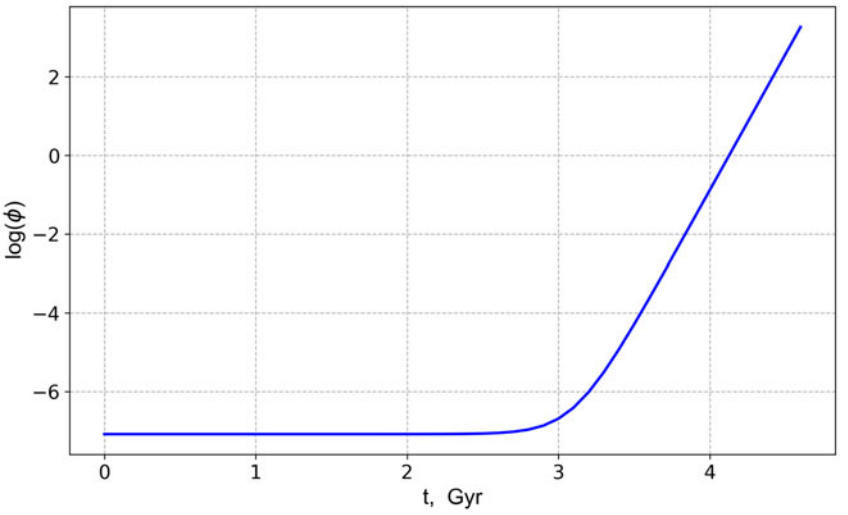


Figure 1. History of crater formation rate on the Moon. ϕ is a number of large (>1 km) craters formed at 1 km^2 area per year. t is given in billion years from our epoch to the past.

where $N(1)$ is the number of craters larger than 1 km formed on the surface of the Moon per 1 km^2 during t, which is given in billion years from our epoch to the past. The time derivative of this function gives an estimate of the bombardment rate (see Fig. 1.)

From Fig. 1 several conclusions can be drawn. First, the rate of bombardment of the Moon as well as the Earth by bodies larger than 50 m (they are believed to be responsible for the formation of impact craters larger than 1 km) has changed little, although ~ 4 billion years ago the rate of bombardment was many orders of magnitude higher. The second, bodies $\geqslant 50$ m collide the Earth on average once every few hundred years. Of course, the estimates obtained above give an estimate of an average rate of bombardment. On scale of billions years various events could cause (temporary) changes in this rate. E.g. estimates of changes in the number of near-Earth objects based on the analysis of the age of lunar craters over the last billion years led Mazrouei et al. (2019); Ipatov et al. (2020) to conclude that the number of collisions per time unit increased 2.6 times about 290 million years ago. The possible cause of such fluctuations is destructive collisions of large bodies. Thus, according to Bottke et al. (2007), the catastrophic destruction of a large Main Belt asteroid occured about 160 million years ago could almost double the number of NEAs larger than 1 km compared to the average number for an interval of 1 billion years. One more reason of fluctuations is dynamic disturbances in the population of minor bodies caused by the Solar System's encounters to stars. In Shustov et al. (2020) it is shown that the Solar System approaches a star (at a distance of $\sim 10^5$ AU) several times (on average 4) over 1 million years. Closer passes of stars at a distance of $\sim 10^3$ AU that cause strong dynamic disturbances in the ensemble of minor bodies of the Solar System occur approximately once every 1–2 billion years.

Since NEAs are responsible for the formation of impact craters on the Moon (the contribution of comets is much smaller) it is logical to compare the statistics of lunar (planetary) data with astronomical data on the NEA size distribution. As noted in Strom et al. (2015), in general, lunar data on the statistics (sizes) of impactors and astronomical data on the NEA size distribution are in good agreement, but they differ significantly from the statistics of the sizes of asteroids of the Main Belt.

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According to Morbidelli et al. (2002) the main source of NEAs ($\sim$ 95%) is the Main Belt (MB), the source of the remaining NEAs is the Kuiper Belt. This means that it is necessary to study the origin and properties of the NEAs together with the study of the entire ensemble of MB asteroids. The interplay between the two populations (NEAs and MB asteroids) include at least the following (obvious) questions:

- how many of the refugees could come back into the MB?
- what is the net asteroid loss rate from the MB (in other words how long MB will survive because of loss of NEAs)?
- what is the dynamic fate of the NEA population?
- etc.

So far, a comprehensive model which could give "all" the answers does not exist although in recent years very interesting models considering some of the issues have been appeared.

Here we focus on dynamic fate of the NEA population. Most remarkable feature is relatively short dynamic time scale (in compare to very long period of constant NEA flux entering Moon surface as it is illustrated in Fig. 1). The elongated orbits of NEAs are subject to strong disturbances from the planets and on this short time scale they either abandon the Solar System or fall onto the Sun and planets or they leave the scope of definition of NEA (NEA zone, where $q \leqslant 1.3$ AU). Unlike the previous two the latter process is not irreversible one. Some NEAs leave the NEA zone, and vice versa some asteroids from the non-NEA area enter NEA zone. For simplicity and by physical analogy we call this phenomenon diffusion in the space of parameters of asteroidal orbits or simply diffusion of orbits.

First estimates of the dynamic scale of the NEA population by Farinella et al. (1994), Gladman et al. (2000), O'Brien et al. (2003) demonstrated that this scale is of order of several million years. Usually the so-called median time, i.e. the time interval during which the population of NEAs is halved, is used to evaluate the scale. We denote this time scale as t_{NEA}. In Gladman et al. (2000), the dynamic evolution of a sample of 117 NEAs was followed over a time interval of 60 million years. It was shown that 10–20% NEAs from the sample end their lives by colliding Venus or Earth, more than half end by falling onto the Sun, and about 15% are ejected from the Solar System. The median lifetime for this sample was estimated $\sim$10 million years. In a more recent paper by Granvik et al. (2018) dynamical evolution of NEA ensemble was studied taking into account their sizes. The authors estimated the average NEO lifetime as $\lessapprox$ 10 million years. Note that definition of lifetime in Granvik et al. (2018) is not same as t_{NEA} defined above, it is a time spent in the parameter region ($q < 1.3$ AU and $a < 4.2$ AU). Dependence of lifetime on asteroid size is not very strong and ranges from about 6 to 11 Myr for asteroids of size 2 – 0.05 km with the mid-sized NEOs having the shortest lifetimes.

We think that it is important to know t_{NEA} more precisely, since this knowledge imposes restrictions on the mechanisms of replenishment of the NEA population, on estimates of the number of NEAs, on the lifetime of MB, etc. In Zolotarev & Shustov (2021), we showed that the lifetime of the current NEA population is about 3 million years. We also noted that the t_{NEA} strongly depends on initial orbital parameters (a, e) of NEAs. In this paper the dependence on the initial parameters of asteroidal orbits is studied in more detail. In section 2 the task formulation and method of modelling are presented; section 3 is devoted to the results obtained. The conclusions are given in section 4.

2. Problem statement and calculation method

One of the tasks of this work was essentially to repeat the t_{NEA} estimate but using complete data set. Currently the number of known NEAs is $\sim$28 000. However this set is obviously incomplete. We have to consider evolution of a group of initially selected

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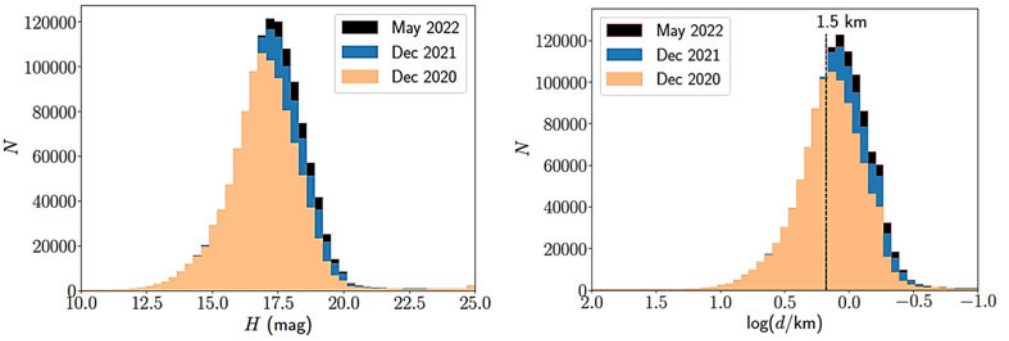


Figure 2. Progress in the knowledge of distribution of MB asteroids by absolute asteroid magnitude H (left) and by size d (right) (data from database of the Minor Planet Center).

NEAs, which is assumed to be statistically complete. It is desirable to have this group as large as possible.

The completeness of the asteriod sample depends on the asteroid size. We believe that for asteroids larger than a certain threshold value the sample can be considered as complete. As it was mentioned in the previous section, to properly study origin and properties of the NEA population which is being permanently replenished from a huge reservoir of MB one needs to model evolution of the entire ensemble of MB asteroids. Again we need to care about completeness of the sample. To estimate the completeness we followed recent changes in size distributions of known MB asteroids. In Fig. 2 the distribution of MB asteroids by absolute asteroid magnitude H and by size is presented. Data were taken from the website of the Minor Planet Center. The dimension (diameter d) of asteroid was determined as in Harris & Harris (1997):

$$d(km) = 10^{3.1236 - 0.5\log_{10}(A) - 0.2H} \tag{2}$$

when the albedo value is assumed to be $A = 0.15$.

It is obvious that increase in the number of asteroids discovered is mainly due to smaller asteroids. Almost all larger asteroids have already been discovered. The limit of "completeness of detection" of MB asteroids according to Fig. 2 is achieved at $d = 1.5$ km. However it would be quite problematic to include all MB asteroids larger than ~1.5 km into integration of dynamics because of their huge number. We somewhat simplified the task and do not consider the whole ensemble of MB asteroids, but smaller subgroup whose completeness of discovery has been achieved even for smaller asteriod size.

Fig. 3 illustrates the progress in knowledge of size distribution of the asteroids which perihelion distances $q < 1.72$ AU. The number of such asteroids is 10 000. As can be seen from Fig. 3, the size limit of completeness of detection for such asteroids is approximately $d = 800$ m.

Taking into account the requirements of the completeness of the sample and limited computing resources, we studied dynamical evolution of 10 000 asteroids larger that 1 km with $q < 1.72$ AU on a time interval of 20 Myr. Note that 833 NEAs larger than 1 km are included and this NEA sample seems to be complete.

We refer to results for NEA subset as Model 1 and for whole sample of 10 000 asteroids as Model 2. The initial distribution of the studied asteroids in the plane of orbital elements $a - e$ is shown in Fig. 4

Integration of asteroids motion was carried out with the REBOUND software package using the hybrid scheme MERCURIUS Rein et al. (2019). We take into consideration the gravitational field of planets and the Sun. In calculations of the sink rates of asteroids

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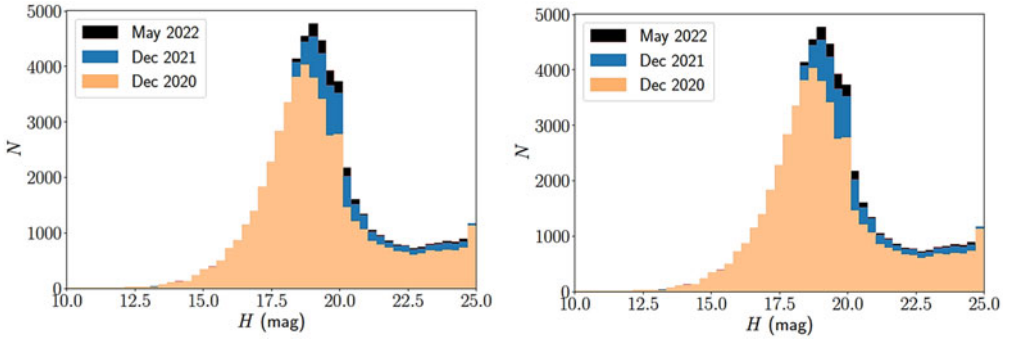


Figure 3. Progress in the knowledge of distribution of MB asteroids with perihelion distances $q < 1.72$ AU.

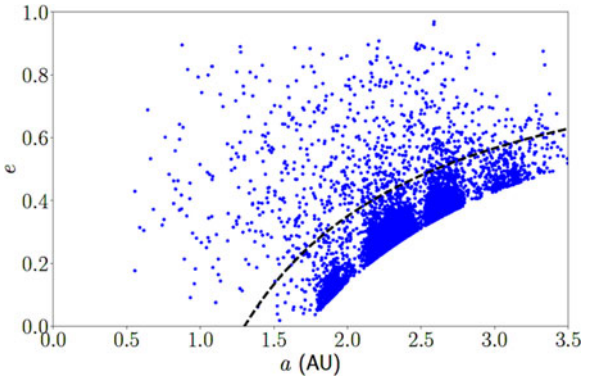


Figure 4. The initial distribution of the studied asteroids larger than 1 km in the plane of the orbital elements $a - e$.

colliding the Sun and planets, we took the geometric dimensions of the objects and neglected sizes of asteroids.

To specify dependence $t_{NEA}\,(a, e, i)$ the entire area of the orbital parameters of the NEA population was divided into cells. Boundary values for cells are given in Tabl.1.

The number of cells is 18. This is a rather rough grid but because of the relatively low total number of NEAs under consideration it does not seem reasonable to increase the number of cells since number of NEAs in a cell would become too small for statistical estimates. The evolution of the ratio N/N_0, i.e. the ratio of the current number of NEAs to the initial number of NEAs in this cell was traced for each cell, and, accordingly, the value of t_{NEA} was determined for each cell.

To illustrate the role of asteroid-planet approaches, the number of approaches of each asteroid to planets was calculated for all asteroids. The approach is considered as an entry event of an asteroid into a zone wich is three times larger than the Hill sphere of the planet. Also in the Model 1 the statistics of NEA loss through various channels (collisions with the Sun, collisions with planets, asteroids leaving the Solar System, asteroids leaving the NEA scope of definition) was followed.

3. Results

In Fig. 5 a time dependence of the ratio of the number of asteroids remained in the NEA zone to the initial number of NEAs at $t = 0$, i.e. $N(t)/N_0$ for Model 1 and Model 2

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Table 1. Boundaries of orbital parameters

a (AU)	0.0, 1.50, 2.25, 3.0
e	0.0, 0.2, 0.7, 1.0
i (degrees)	0, 20, 180

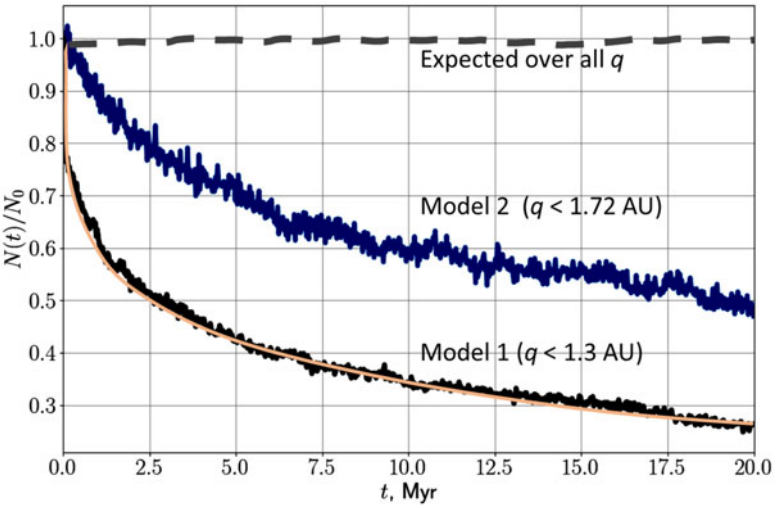


Figure 5. The ratio $N(t)/N_0$ for the NEA ensemble (Model 1) and for the extended set of asteroids (Model 2). The smooth line represents the approximation (3) for Model 1.

are shown. For Model 1 $t_{NEA} \approx 3.0$ million years. The dependence $N(t)/N_0$ in Model 1 is well approximated by the expression

$$\frac{N(t)}{N_0} = e^{-0.5t^{0.33}}, \tag{3}$$

where the time t is given in million years.

Fig. 5 also shows the dependence $N(t)/N_0$ in the Model 2. This value decreases much more slowly over time, which is naturally explained by the fact that there is a significant reservoir of asteroids in the $q < 1.72$ AU zone from which asteroids can "diffuse" into the NEA zone. If one will take into consideration the total reservoir of MB asteroids, then the curve will be flat at the level of $\simeq 1$ (in Fig. 5 is shown by a dashed line).

The dependence of $t_{NEA}(a, e, i)$ is illustrated in Fig. 6.

From Fig. 6 the following conclusions can be drawn:

• the values of t_{NEA} are significantly higher for NEAs whose orbits originally had higher i. Qualitatively this can be explained by the fact that asteroids in these orbits have fewer close approaches to planets.

• the higher values of a and e the lower t_{NEA} is lower for higher values of a and e. Bodies at such orbits have more approaches to the most powerful disturbing body – Jupiter.

It seems to be natural to compare $t_{NEA}(a, e, i)$ and the frequency of approaches N_{enc}. In Fig. 7 numbers of approaches for asteroids from different cells on the orbital parameters plane $a - e$, are given at the time of 12 million years. We checked that the picture does not change even for a larger time interval of integration.

Since the number of approaches can be quite large it is reasonable to split the plane $a - e$ into a larger number of cells in compare to Fig. 6. The upper panel of the figure 7

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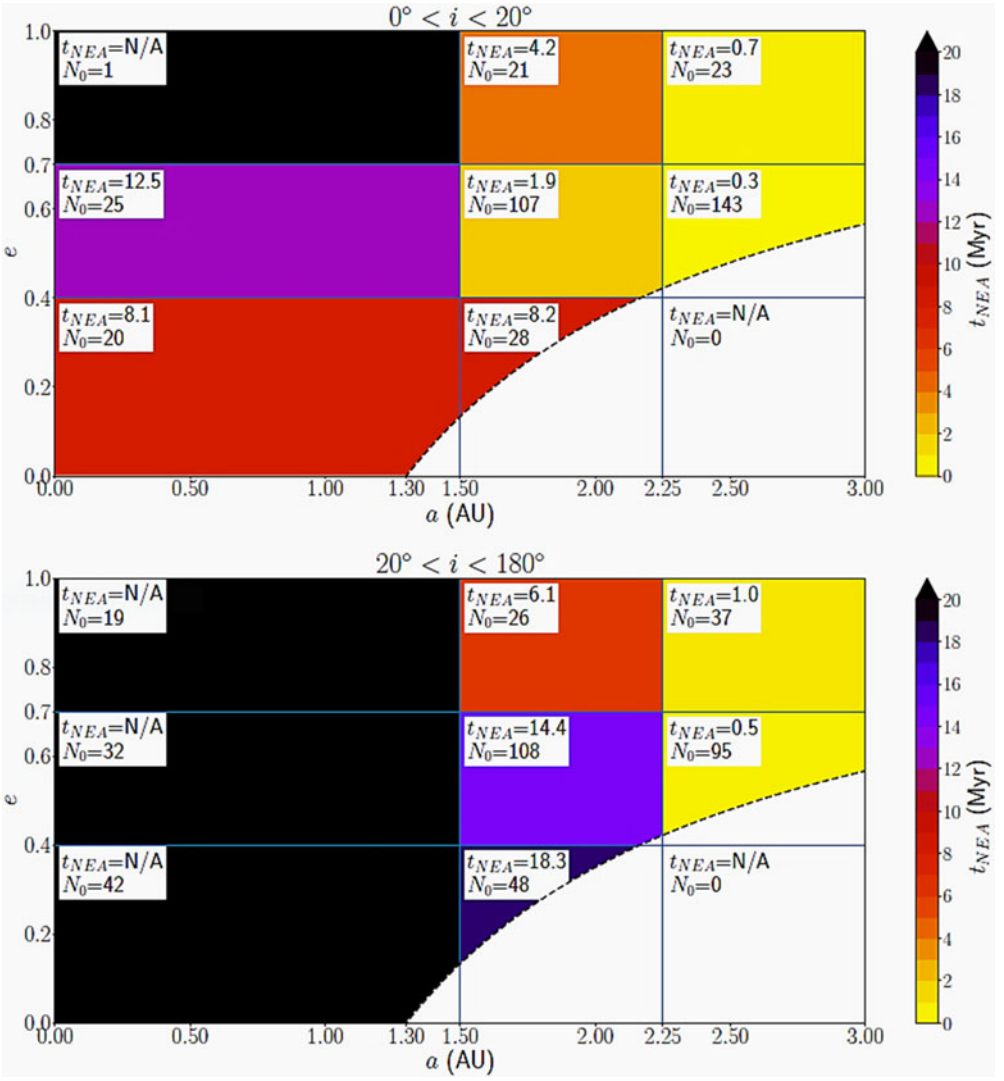


Figure 6. Dependence of $t_{NEA}(a, e, i)$ on the orbital parameters for cells of the parameters. t_{NEA} (in million years) and the number of asteroids N_0 at the time $t_0 = 0$ are indicated for each cell. In black-colored zones, t_{NEA} exceeds 20 million years.

shows the total number of approaches to the planets of asteroids located in this cell. At the lower panel, this value is normalized to average number of asteroids in this cell, i.e. the panel shows an average number of approaches for each asteroid from this cell. A prominent detail in Fig. 7 is an increased number of approaches (both general and relative) for asteroids which perihelion distance is $q = 0.72$ AU and $q = 1.0$ AU as well as those with the aphelion distance $Q = 1.0$ AU. This is due to the fact that such asteroids relatively more frequently approach Venus and the Earth respectively. The increased frequency of approaches seen in the upper right corner of the Fig. 7 is explained by the fact that asteroids in such elongated orbits with large a relatively frequently approach Jupiter in the aphelion region of their orbits.

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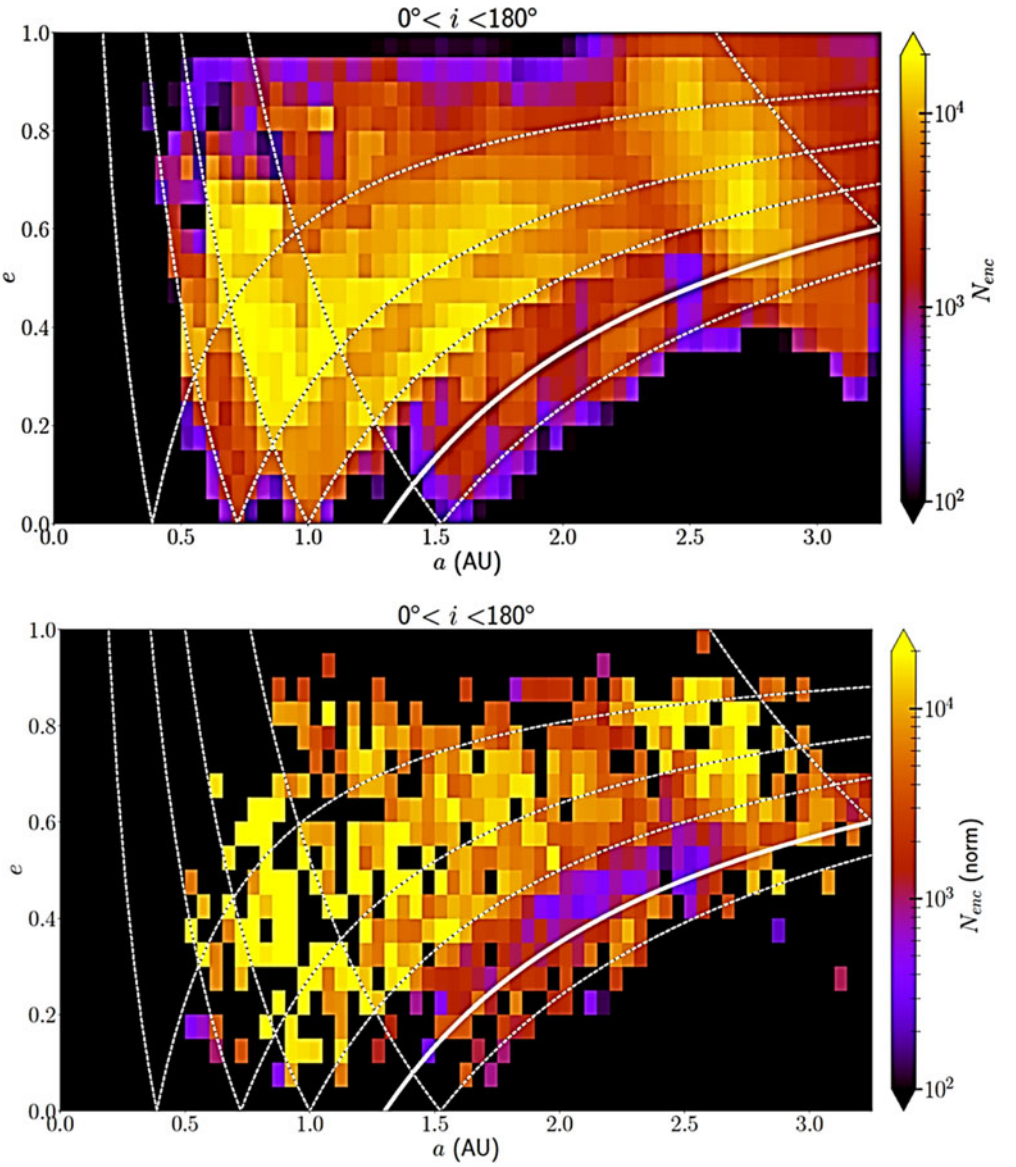


Figure 7. The number of approaches to planets for asteroids from different cells on the plane of the orbital parameters $a-e$ at the time $t=12$ million years. The top panel shows the total number of approaches for each cell. On the bottom panel - the normalized number of approaches (approaches per asteroid). The dotted lines correspond to the perihelion distance $q=0.387, 0.723, 1.0, 1.523$ AU, as well as the aphelion distance $Q=0.387, 0.723, 1.0, 1.523, 5.203$ AU. The bold white line shows the border of the NEO zone ($q=1.3$ AU).

As it was mentioned above the rates of escape of asteroids from NEA zone via various escape channels were followed. Fig. 8 shows the time dependence of the number $N(t)$ of asteroids (relative to the initial number of N_0) leaving the NEA zone (Model 1). Number of irretrievably lost asteroids (due to ejection from the Solar System, collisions with planets or the Sun) monotonously increases. At $t=20$ million years the share of NEAs abandoned the Solar System is 7%, collided planets – 4%, collided the Sun – 15%, ejected

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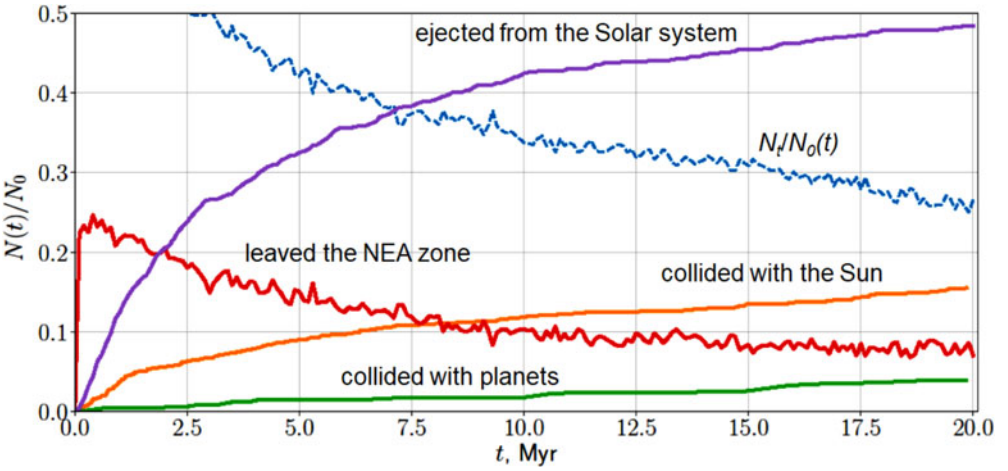


Figure 8. Loss of asteroids from NEA zone via various channels in the process of dynamical evolution (Model 1). $N(t)/N_0$ – ratio of cumulative number of asteroids lost via a given channel at time t to is number of asteroid at $t = 0$. The dashed line is the same dependency as shown in Fig. 4 (Model 1).

from the Solar System – 48%. Major share of collisions occur with the Sun, which was also noted in Farinella et al. (1994).

4. Conclusions

In this paper we quantitatively study the dependence of the loss rate of larger NEAs on the position of asteroids in the space of initial orbital elements (a, e, i). Estimate for the loss time scale (t_{NEA}) is obtained. The main channels of NEAs loss are considered. The results obtained can be used in the future study of mechanisms of replenishment of the NEA population a well as for the study of MB fate.

Dependence of t_{NEA} on initial orbital parameters of NEAs is strong and the t_{NEA} for different regions of the phase space may differ more that order of magnitude. On the other hand the distribution of NEAs in a phase space seems to remain stable for a long time. Hence to consider mechanisms of replenishment one needs to take into account this result as a boundary condition of stationarity. The dependence of t_{NEA} on the asteroid size has not been studied in this work. As shown in Granvik et al. (2018), the dynamic fate of an asteroid of size in range $\simeq 2 - 0.05$ km depends on the size (to a relatively lesser extent then for orbital parameters). Most important factor was considered to be the Yarkovsky effect. In this paper we consider dynamics of larger (> 1 km) asteroids. For these asteroids Yarkovsky effect is relatively weak ($\mathrm{d}a/\mathrm{d}t < 10^{-9}$ AU/yr). In future models we plan to expand the list of NEAs by adding smaller asteroids, but requirement of completeness of the sampe remains. Then this dependence on size is to be taken into account.

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