Fugitives from the Hungaria Region: close encounters and impacts with terrestrial planets.

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Abstract

Hungaria asteroids, whose orbits occupy the region in element space between $1.78 < a < 2.03$ AU, $e < 0.19$, $12^\circ < i < 31^\circ$, are a possible source of Near-Earth Asteroids (NEAs). Named after (434) Hungaria these asteroids are relatively small, since the largest member of the group has a diameter of just about 11 km. They are mainly perturbed by Jupiter and Mars, possibly becoming Mars-crossers and, later, they may even cross the orbits of Earth and Venus. In this paper we analyze the close encounters and possible impacts of escaped Hungarias with the terrestrial planets. Out of about 8000 known Hungarias we selected 200 objects which are on the edge of the group. We integrated their orbits over 100 million years in a simplified model of the planetary system (Mars to Saturn) subject only to gravitational forces. We picked out a sample of 11 objects (each with 50 clones) with large variations in semi-major axis and restarted the numerical integration in a gravitational model including the planets from Venus to Saturn. Due to close encounters, some of them achieve high inclinations and eccentricities which, in turn, lead to relatively high velocity impacts on Venus, Earth, and Mars. We statistically analyze all close encounters and impacts with the terrestrial planets and determine the encounter and impact velocities of these fictitious
Hungarias.

Keywords: Hungaria, NEAs, close encounters, impacts

1. Introduction

For the purposes of this paper we consider as belonging to the Hungaria group the asteroids whose orbital elements are in the range $1.78 \text{(AU)} < a < 2.03 \text{(AU)}$, $12^\circ < i < 31^\circ$ and $e < 0.19$, so that our sample finally consists of 8258 asteroids; the orbital data were taken from the ASTORB database (http://www2.lowell.edu/elgb, updated August 2010). This orbital region is confined by the $v_6$ secular resonance and by the mean motion resonances 4:1 with Jupiter and 3:4 with Mars.

There is evidence that some meteorites may originate from the Hungarias. This is deduced in the first place from the spectra of the majority of the Hungarias; about 77% of them are of the E-type, 17% belong to the S-type and 6% to the C-type [19]. The E-type asteroids are consistent with the composition of some meteorites (aubrites, Zellner et al. [21]) found on the Earth.

Because of their typical composition, the Hungarias have an average albedo of $p_v \sim 0.4$ (Warner et al. [19], hereafter abbreviated as WH), which distinguishes them from other asteroids in the main belt having $p_v \sim 0.18$ or lower.

The largest member of the group, (434) Hungaria, has a diameter of just about 11 km [14].

The majority of Hungarias have a retrograde rotation and similar spin rates [15, 16]. Warner and Harris [18] found a consistent group of binaries (more than 10%) with fast rotating primaries, this presence being a sign of a collisional origin [5, 20]. Based on the study of Lemaitre & Morbidelli [11] on proper elements
WH assumed that the Hungarias formed after a catastrophic collision of (434) Hungaria, presumably the largest fragment of the Hungaria collisional family. Starting from this collisionary assumption they computed an age for the family of about 0.5 Gy, that comes from the degree of spreading versus size of family members. WH, considering 2859 family members, found a value of 26 km for the diameter of the putative parent body.

Milani et al. [13] confirmed this collisional origin, underlining the possibility of the presence of a subfamily, especially for the uniform number distribution in semi-major axis for values above 1.92 AU. They suggested a half life of 960 My and a diameter of 30 km for the parent body, this latter value in good agreement with WH. Bottke et al. [2], in contrast to the previous suggestions about the origin, assumed that the Hungarias evolved from the depletion of a part of the primordial main belt with semi-major axes between 1.7 AU and 2.1 AU.

In the rest of this paper we present the results of our statistical investigation of the close encounters of the escaped Hungarias with the terrestrial planets, in a model including only gravitational interactions. The methods used are described in section 2; the results are shown in section 3 and in section 4 we discuss the production of NEAs from the Hungaria population. The conclusions are in section 5.

2. Methods

Out of our 8258 Hungarias, we selected 200 according to a criterion based on the action variables (semi-major axis, $a$, eccentricity, $e$ and inclination, $i$ of the asteroid); we chose the following variable:
\[
d = \sqrt{\left(\frac{e}{<e>}\right)^2 + \left(\frac{a}{<a>}\right)^2 + \left(\frac{\sin i}{<\sin i>}\right)^2}
\]

and picked up the 200 Hungarias with the highest values of \(d\).

Our study of the dynamical transport to the terrestrial planets and the possible impacts was performed in two steps:

1. We integrated the orbits of the 200 asteroids in a simplified dynamical model for the solar system (Sun, Mars, Jupiter, Saturn and the massless asteroids) for 100 million years (My) to identify possible escapers (that from now on we call “fugitives”), based on the variation in of the semi-major-axis; in this way we identify 11 fugitives.

2. The 11 fugitives found (see Table 1) were then cloned, adding to each of them 49 additional sets of initial conditions (see later). We integrated the 550 objects in a model Solar System including the planets from Venus to Saturn, again for 100 My; all the results presented in the paper referred to the outputs of these integrations.

All the integrations have been done using the Lie-series integrator [6, 9].

The criterion of selection for the fugitives was to check whether the excursion in semi-major axis \(\Delta a = a_{\text{max}} - a_{\text{min}}\) for an individual object was \(\Delta a > \Delta a_{\text{group}}/16 = 0.0156\) AU, where \(\Delta a_{\text{group}}\) corresponds to \(\sim 7\%\) of the total range of semi-major axis spanned by the Hungarias.

For the generation of clones, we generated random values for \((a, e, i)\), starting with the initial conditions of the escapers in the following ranges: \(a \pm 0.005\) AU, \(e \pm 0.003\) and \(i \pm 0.005^\circ\).

It turns out that the 11 fugitives belong to the Hungaria family (see the AstDyS website, http://hamilton.dm.unipi/astdys, for comparisons with the elements), so
we can speak about fugitives from the Hungaria family. Two of them (30935) Davasobel, and (211279) 2002 RN\textsubscript{137} are also present in the list of [13] for the Hungaria asteroids in strongly chaotic orbits.

All the data relative to the close encounters with the terrestrial planets were stored for later examination; for the Earth we took as close encounter limiting distance the average lunar distance, $2.50 \cdot 10^{-2}$ AU, for Mars and Venus, we used a distance scaled in proportion to the ratio of their Hill spheres with respect to the one of the Earth, namely $1.70 \cdot 10^{-2}$ AU for Venus and $1.66 \cdot 10^{-2}$ AU for Mars.
3. RESULTS

Once our fugitives have left the Hungaria region, their orbital evolution becomes strongly chaotic and is strongly affected by close encounters with one or more of the terrestrial planets.

(211279) 2002 RN\textsubscript{137} is one example for these Hungarias fugitives that becomes NEA: it changes from one NEA-type to another, starting to be an Amor at 64.015 My and then an Apollo for the first time at 72.669 My.

We found that, when the fugitives start to be NEAs, some observed NEAs pass through similar semi-major axis and eccentricities. In fact, more than 70\% of the clones are inside these ranges: \(1.71 < a < 2.04\) (AU) and \(0.21 < e < 0.38\), with a peak around \(1.92 < a < 2.04\) (AU) and \(0.32 < e < 0.38\); inside the first range we have \(\sim 880\) known NEAs, while inside the second one we find 61 known NEAs (from \texttt{http://ssd.jpl.nasa.gov/sbdb_query.cgi\#.x}, JPL Small-Body Database Search Engine). In particular we mention 143409 (2003 BQ\textsubscript{46}), 249595 (1997 GH\textsubscript{28}) and 285625 (2000 RD\textsubscript{34}), because they are inside the range of the absolute magnitude in visual (\(H_V\)) of Hungarias, \(14 < H_V < 18\) (for details see Fig.3 of \cite{19}).

3.1. Close encounters

The sample of Hungarias which we used has a high probability (> 77\%) to have close encounters (CEs) with terrestrial planets, especially with Mars, in the 100 My time interval. We show the detailed results in Tab.\textsuperscript{2} counting the CEs for every planet separately (first three columns) and the CEs (last three columns) exclusively to only one of the terrestrial planets.
Table 2: Close encounters for the sample of 550 Hungarias during 100 My with the terrestrial planets. Columns 2 to 4 for every planet separately, Columns 5 to 7 for a planet alone. “N.” stands for number and “%” for percentage.

|                  | Close encounters to . . . | Close encounters only to . . . |
|------------------|---------------------------|-------------------------------|
| Mars Earth Venus | N. 427 158 132            | Mars Earth Venus              |
|                  | % 77.6 28.7 24.0          | 243 0 0                       |
|                  |                           | 44.2 0.0 0.0                  |

Not surprisingly, most of the fictitious asteroids have CEs with Mars. The CEs to Earth and Venus tend to take place in the expected order, because the dynamical transport the inner system needs more time for Venus than for the Earth and Mars. Almost half of our bodies just meet Mars and then undergo either an ejection or a collision with the Sun (see later). None of them have only CEs with the Earth and only one of them has CEs exclusively with Venus and the Earth; 3 of them have CEs exclusively with Mars and Venus.

In the first three columns of Tab. 3 the encounter probabilities for two of the planets are not so different for any pair and also not for CEs with all the three planets. The possibility that an object meets only a specific pair is very low especially for Mars-Venus and Earth-Venus, but it is more probable for Mars-Earth.

In Tab. 4 one can see that the average time for a first close encounter with Venus is quite long (∼ 63 My), but it is somewhat surprising that this time is not much smaller for the Earth (∼ 62 My). For the first CE with Mars the average time is very low (∼ 14 My); we already explained it with the relative closeness of the semi-major axes of Mars with the perihelion distances of the Hungarias.
Table 3: Close encounters for the sample of 550 Hungarias during 100 My with the terrestrial planets. Columns 2 to 4 for at least two planets and columns 5 to 7 ONLY for two planets. M stands for Mars, E for the Earth and V for Venus. “N.” stands for number and “%” for percentage.

|                | close encounters to pair . . . | close encounters only to pair . . . |
|----------------|---------------------------------|------------------------------------|
|                | M & E   | M & V   | E & V   | M & E & V | M & E   | M & V   | E & V   |
| N.             | 143     | 122     | 119     | 138       | 24      | 3       | 1       |
| %              | 26.0    | 22.2    | 21.6    | 25.1      | 4.4     | 0.6     | 0.2     |

In Tab. 5 the average time $\langle T_{pl} \rangle$ for an object to become member of a NEA type (i.e. Amor, Apollo, Aten and IEO) is listed. These four groups are defined as follows:

- **IEOs (Inner Earth Orbits)** NEAs whose orbits are contained entirely with the orbit of the Earth with $a < 1.0$ AU, $Q < 0.983$ AU
- **Atens** Earth-crossing NEAs with semi-major axes smaller than Earth’s, named after (2062) Aten – with $a < 1.0$ AU, $Q > 0.983$ AU
- **Apollos** Earth-crossing NEAs with semi-major axes larger than Earth’s, named after (1862) Apollo, with $a > 1.0$ AU, $q < 1.017$ AU
- **Amors** Earth-approaching NEAs with orbits exterior to Earth’s but interior to Mars, named after (1221) Amor, with $a > 1.0$ AU, $1.017(AU) < q < 1.3(AU)$

1Sometimes we will call them also Atiras.
| Planet  | $\langle T_{pl} \rangle$ [My] | $T_{pl,\text{min}}$ [My] |
|---------|-----------------------------|--------------------------|
| Venus   | 63.34                       | (41577) 2000 SV$_2$ 10.9 |
| Earth   | 62.45                       | (152648) 1997 UL$_{20}$ 10.5 |
| Mars    | 13.51                       | (24883) 1996 VG$_9$ 0.07 |

Table 4: Average value of the time of the first CE with the planets for all objects (2$^{nd}$ column) and for the shortest time of a first CE with the planets for a single object 3$^{rd}$ column.

| Family | $\langle T \rangle$ [My] | $T_{\text{min}}$ [My] |
|--------|---------------------------|------------------------|
| Amor   | 46.67                     | (41577) 2000 SV$_2$ 0.09 |
| Apollo | 60.82                     | (152648) 1997 UL$_{20}$ 1.68 |
| Aten   | 61.44                     | (152648) 1997 UL$_{20}$ 8.40 |
| Atira  | 69.37                     | (152648) 1997 UL$_{20}$ 8.92 |

Table 5: $T$ is the average time (of the real asteroid and the clones) when the object becomes member of the NEA family, $T_{\text{min}}$ is the minimum time for the indicated object.

The Table shows how $\langle T_{pl} \rangle$ increases going from the outer NEAs (the Amors) to the inner ones (the IEOs).

In Tab.6 we show the percentage of the clones which collide with the Sun. In particular the clones of (41577) 2000 SV$_2$ have the highest probability to hit the Sun, while also (152648) 1997 UL$_{20}$, (141096) 2001 XB$_{48}$ and (39561) 1992 QA have high chances to do so (Table 6).

According to our statistics we can say that about 18% from the escaping Hungarias end up as Sun colliders within 100 My.

From the first sample (200 fictitious asteroids out of $\sim$ 8000) we found only
| Asteroid           | Imp. Sun %/100My | $\langle P \rangle$ [AU/100My] | $q$ [AU] |
|-------------------|------------------|------------------------------|---------|
| (211279) 2002 RN_{137} | 4                | 0.90 ± 0.33                 | 0.00    |
| (41898) 2000 WN_{124} | 0                | 1.55 ± 0.07                 | 1.02    |
| (39561) 1992 QA    | 22               | 0.96 ± 0.30                 | 0.00    |
| (30935) Davasobel  | 14               | 0.69 ± 0.19                 | 0.00    |
| (171621) 2000 CR_{58} | 2               | 1.61 ± 0.17                 | 0.00    |
| (152648) 1997 UL_{20} | 36              | 0.82 ± 0.34                 | 0.00    |
| (141096) 2001 XB_{48} | 50              | 0.54 ± 0.23                 | 0.00    |
| (24883) 1996 VG_{9}  | 4                | 1.37 ± 0.07                 | 0.00    |
| (41577) 2000 SV_{2}  | 40               | 0.68 ± 0.37                 | 0.00    |
| (129450) 1991 JM    | 4                | 1.20 ± 0.20                 | 0.00    |
| (175851) 1999 UF_{5} | 20              | 1.07 ± 0.28                 | 0.00    |

Table 6: Number of clones per 100 My per asteroid that end up as sun-impactors (we assume an impact with the Sun at whenever its perihelion is less than 0.0047 AU, approximately the radius of the Sun) with the average and the minimum perihelion of their clones.
| Family/group       | T [My] | a [AU] | e   | i [deg] | T. Par. | Var. in % |
|-------------------|--------|--------|-----|---------|---------|-----------|
| (211279) 2002 RN$_{137}$ |        |        |     |         |         |           |
| Hungaria          | 0      | 1.8552 | 0.1175 | 22.82  | 1.51625 | 0.0       |
| First enc. Mars   | 0.050  | 1.8551 | 0.1625 | 25.46  | 1.48297 | 2.2       |
| leaves Hungarias  | 0.063  | 1.8540 | 0.1904 | 23.47  | 1.49585 | 1.4       |
| NEA - Amor        | 64.016 | 1.7817 | 0.2719 | 29.09  | 1.40315 | 7.5       |
| NEA - Apollo      | 72.670 | 1.8166 | 0.4478 | 28.23  | 1.33699 | 11.9      |
| (41577) 2000 SV$_2$ |        |        |     |         |         |           |
| Hungaria          | 0      | 1.8517 | 0.1850 | 24.97  | 1.48231 | 0.0       |
| leaves Hungarias  | 0.004  | 1.8517 | 0.1988 | 24.16  | 1.48684 | 0.3       |
| NEA - Amor        | 0.085  | 1.8490 | 0.2991 | 24.29  | 1.45306 | 2.0       |
| First enc. Mars   | 0.226  | 1.8501 | 0.2331 | 23.25  | 1.48553 | 0.2       |
| First enc. Earth  | 77.926 | 2.0553 | 0.5048 | 3.98   | 1.47785 | 0.3       |
| First enc. Venus  | 78.544 | 2.1634 | 0.7259 | 5.61   | 1.23792 | 16.5      |
| NEA - Apollo      | 77.889 | 2.0485 | 0.5036 | 0.73   | 1.48050 | 0.1       |
| Sun-impact        | 85.545 | 2.3541 | 0.9999 | 20.89  | 0.23267 | 84.3      |

Table 7: Dynamical evolution for clones (211279) 2002 RN$_{137}$ and (41577) 2000 SV$_2$ describing to which asteroid group the objects belong to; in addition the semi-major axes a, the eccentricity e, the inclination i and the Tisserand parameter and its variation are given in columns 3 to 6.
5% of escapers, so our estimate of an upper limit of Sun-impactor Hungarias in the time scale of 100 My is 0.98%, instead for the planet’s impacts (0.23%). Only a very minor fraction escape beyond Jupiter’s orbit and become Centaurs and afterwards Trans-Neptunian Objects (TNOs), just < 1% of them.

3.2. Analysis of close encounter data

As an example of the dynamical evolution we discuss two examples out of our sample, (211279) 2002 RN$_{137}$, that ends as member of the Apollo group, and (41577) 2000 SV$_{2}$, that has an impact on the Sun. Both show the characteristic behaviour of changing the group membership inside the NEAs. In Tab.[7] details on the escape times from the Hungaria region of these two asteroids are given. Here “escapers” mean that the Hungarias’ orbital elements ($a, e, i$) fall outside the range of semi-major axes $a$, eccentricity $e$, or inclination $i$ defined in section [2].

In general, the fugitives leave the group very soon, sometimes in less than $10^{5}$ years, apart from (41898) 2000 WN$_{124}$, that has only 5 clones which escape after CEs to Mars. If the escapers have CEs with Mars, they also become NEAs (Table [4] note that here the ones that becomes soon NEAs have a higher probability than the others to become sun grazers, e.g. (41577) 2000 SV$_{2}$, Table [7], in particular Apollos and Amors, but changing orbital type during the last millions of years of the integration. Shoemaker [17] showed, that asteroids frequently change the NEA family due to their chaotic orbits.

When belonging to the Amor group within 11 My (average on the whole) or less, they become Apollos, and in many cases also Atens and Atiras, e.g. (152648) 1997 UL$_{20}$, whose clones have a huge number of close encounters with all the terrestrial planets. Their eccentricities will raise up after close encounters with Mars, and then impacts on all terrestrial planets are possible, even on the Sun.
Observing the average inclination in Table 10, the inclination of the asteroids that have very likely become NEAs, like (211279) 2002 RN137, (30935) Davasobel and (39561) 1992 QA, increases.

It is interesting to see that the normalised Tisserand parameter \( T_{\text{ast}} = 1 + \frac{1}{a} + \sqrt{a(1-e^2)\cos(i)} \), where \( a \) is the semi-major axis of the asteroid orbit, \( e \) the eccentricity and \( i \) the inclination) stays almost constant after different close encounters also with the Earth: see Table 7, where in the last column where we have put the variation in percentage of the first value. Till the asteroid is not a NEA, the parameter does not vary more than 2% and stays close to the average value for the Hungaria family, that is 1.546 ± 0.017 which, just for comparison to the value for the Vesta 1.740 ± 0.006 (from data by [7]), is much lower.

From the close encounters we derive information about the duration (time while the body enters and exits from the region defined for a close encounter for each planet, see section 2) and the relative velocity in front of each terrestrial planets. This last one will be compared with the relative velocity of the observed NEAs.

We study the relation between the duration and the absolute number of close encounters, with one or more terrestrial planets. We underline that the mean duration of close encounters depends on how many planets the Hungaria-fugitive can approach: more often planets are reached, shorter are the duration of the encounters.

In fact for those objects that have the lowest probability to have close encounters we find a bigger duration, i.e. the maximum value with Mars is for (41898) 2000 WN124 (0.65 d), which also has only a small probability to have a close approach with the planet, and does not approach the other two planets.
Of course the singular event depends mainly on the entry velocity. The “entry velocity” is the velocity of the asteroid when it arrives for the first time at the maximum distance established for a close encounter from the planet.

On average the mean duration of close encounters with Mars is about half a day, and this is the highest value for the terrestrial planets. In summary: $0.27 \pm 0.05\,\text{d}$ for Venus, $0.36 \pm 0.09\,\text{d}$ for Earth and $0.55 \pm 0.05\,\text{d}$ for Mars.

The Hungaria-fugitives seem to have more close encounters, even if the scattering of encounters’ mean is relatively high, with the Earth respect to the other planets. In fact the average number of close encounters for each terrestrial planet in 100 My of orbit-evolution is for Mars 57, for the Earth 77 and for Venus 42, even if almost all of them has a close encounter with Mars, but not with the other two terrestrial planets (see Table 2).

The average deflection angle $\Theta$, i.e. the angle between the direction of the entry velocity vector and the one of the exit velocity vector, is usually very small ($< 1^\circ$), though in some cases we get values of more than $60^\circ$, and even more than $90^\circ$ like for (129450) 1991 JM.

The mean entry velocities for the fugitives are compared with the mean velocity of the real known asteroids with respect to each planet.

In order to compute the relative velocity of the known asteroids in front of the planets we considered

- as Venus-crossers: IEOs (the ones with $Q \geq 0.718\,\text{AU}$), Atens (the ones with $q \leq 0.728\,\text{AU}$) and Apollos (the ones with $q \leq 0.728\,\text{AU}$);

- as Earth-crossers: Atens and Apollos;

- as Mars-crossers: Mars crossing asteroids (the non-NEA ones with $1.300(AU) <$
\[ q < 1.666(\text{AU}) \text{ and } a < 3.2 \text{ AU}, \] and all the NEAs with \( Q \geq 1.381 \text{ AU} \) (so no IEOs, but a part of the other NEA-types).

The close encounter velocity of the real asteroids \((v_r)\) is computed with the next equations:

\[ v_r = U v_{planet} \]

\[ v_{planet} = \sqrt{\frac{G(M_{sun} + M_{planet})}{r_{planet}}} \]

\[ U = \sqrt{3 - T_{planet}} \]

\[ T_{planet} = \frac{a_{planet}}{a_{ast}} + 2 \sqrt{\frac{a_{ast}}{a_{planet}}(1 - e_{ast}^2)} \cos i_{ast} \]

Where \( G, M_{sun}, M_{planet} \) and \( r_{planet} \) are respectively the gravitational constant, the mass of the Sun, the mass of the planet, and the heliocentric distance of the planet from the Sun, assumed as the semi-major axis of the planet, all values in SI, the international system of measures. \( U \) is the adimentional encounter velocity at infinitum computed via the Tisserand parameter \((T_{planet})\) in respect to the relative planet. \( a_{planet} \) is the semi-major axis of the relative planet, to which we compute the parameter, and the remnants values are the other osculatory elements of each asteroids to compare to the relative planet.

We take in account of the circular orbital velocity of each planet \((v_E = 29.7892, v_M = 24.1333 \text{ and } v_V = 34.9084, \) respectively for the one of the Earth, Mars and Venus, all in km/s).

By our results the encounter velocity is greater for Hungarias than the mean,
| Sample            | $<v_{r,Venus}>$ | $<v_{r,Earth}>$ | $<v_{r,Mars}>$ |
|-------------------|-----------------|-----------------|----------------|
| Hungaria fugitives| 27.80 ± 1.71    | 21.54 ± 2.30    | 10.85 ± 1.01   |
| Real asteroids    | 21.66 ± 8.69    | 15.18 ± 7.35    | 10.83 ± 4.99   |

Table 8: Average velocity of the asteroids in respective to Venus, the Earth, and Mars and standard deviation. The first row is the average of the entry velocity of the all Hungaria fugitives clones per planet, the second one is the average of the real asteroids that cross the orbit of the planets.

especially for Venus and the Earth, Mars is pretty the same, despite the high standard deviation. The values would give a more probable larger impact velocities in case of an impacts than the average one found for all type of impactors, so it seems that possible Hungarias’ impactors are faster than the average.

4. Hungarias as a source of NEAs

4.1. Evolution when in NEA orbits

Some fugitives start to be NEAs quite soon with a peak on their rate distribution during their orbital evolution, around 60 My, as it can be seen clearly from Fig. [1]. In this histogram the value $N$ is equal to the normalized number of asteroids per each time, found with this equation:

$$N = \frac{N_{c-n}}{N_c} \frac{N_f}{N_s}$$

$N_{c-n}$, $N_c$, $N_f$ and $N_s$ are respectively the number of Hungaria-clones (HCs) which has become NEAs, the total number of HCs at the beginning of the orbital evolution, the number of the fugitives (Hungarias escaped from the initial sample
Table 9: Data of the planetary close encounters for some of the 11 Hungaria fugitives. All the velocities were measured at the distance for an encounter relative to the planet (2.50 \cdot 10^{-2} \text{ AU} for the Earth, 1.70 \cdot 10^{-2} \text{ AU} for Venus and 1.66 \cdot 10^{-2} \text{ AU} for Mars, as defined in section 2): $\bar{v}_{\text{en}}$ is the mean entry velocity, $\bar{v}_{\text{en, max}}$ is the mean maximum entry velocity, $\bar{v}_{\text{en, min}}$ is the mean minimum entry velocity. We found that the exit velocity is always equal to the entry velocity inside a range of 0.01 km/s.

| Planet | Ast. | $\bar{v}_{\text{en}}$ | $\bar{v}_{\text{en, max}}$ | $\bar{v}_{\text{en, min}}$ |
|--------|------|------------------------|-----------------------------|-----------------------------|
| Venus  | (211279) 2002 RN$_{137}$ | 27.32 $\pm$ 7.42 | 35.10 | 19.26 |
|        | (30935) Davasobel       | 29.76 $\pm$ 7.38 | 37.42 | 24.38 |
|        | (39561) 1992 QA         | 29.28 $\pm$ 11.67 | 42.03 | 22.66 |
| Earth  | (211279) 2002 RN$_{137}$ | 20.03 $\pm$ 6.64 | 29.94 | 12.60 |
|        | (30935) Davasobel       | 20.36 $\pm$ 6.07 | 28.64 | 16.54 |
|        | (39561) 1992 QA         | 22.32 $\pm$ 12.17 | 31.32 | 13.05 |
| Mars   | (211279) 2002 RN$_{137}$ | 10.71 $\pm$ 1.71 | 16.63 | 5.96 |
|        | (30935) Davasobel       | 13.15 $\pm$ 1.72 | 19.12 | 7.91 |
|        | (39561) 1992 QA         | 11.05 $\pm$ 1.50 | 16.29 | 7.14 |
| Planet | Ast. | $\bar{i}_{en}$ | $\bar{i}_{en,\text{max}}$ | $\bar{i}_{en,\text{min}}$ | $\bar{i}_{ex}$ | $\bar{i}_{ex,\text{max}}$ | $\bar{i}_{ex,\text{min}}$ |
|--------|------|----------------|-----------------|----------------|----------------|-----------------|----------------|
| Venus  | 1    | 25.80 ± 14.42 | 36.30           | 15.31          | 25.82 ± 14.38 | 36.30           | 15.35          |
|        | 2    | 26.16 ± 14.43 | 39.43           | 16.68          | 26.15 ± 14.41 | 39.47           | 16.67          |
|        | 3    | 23.94 ± 20.60 | 33.47           | 17.88          | 23.91 ± 20.62 | 33.28           | 17.88          |
| Earth  | 1    | 22.72 ± 12.55 | 36.29           | 11.13          | 22.66 ± 12.62 | 36.32           | 11.05          |
|        | 2    | 25.61 ± 11.23 | 36.85           | 18.92          | 25.51 ± 11.26 | 36.69           | 18.91          |
|        | 3    | 27.34 ± 22.88 | 39.25           | 15.72          | 27.39 ± 22.96 | 39.20           | 15.77          |
| Mars   | 1    | 23.26 ± 4.14  | 33.76           | 12.44          | 23.26 ± 4.14  | 37.72           | 12.43          |
|        | 2    | 27.00 ± 4.67  | 38.59           | 15.66          | 27.00 ± 4.68  | 38.59           | 15.66          |
|        | 3    | 23.85 ± 3.40  | 32.15           | 16.01          | 23.85 ± 3.40  | 32.15           | 16.02          |

Table 10: Data of the planetary close encounters for some of the 11 Hungaria fugitives (1 = (211279) 2002 RN137, 2 = (30935) Davasobel and 3 = (39517) 1992 QA. All the inclinations were measured at the distance for an encounter relative to the planet (2.50 $\cdot$ 10$^{-2}$ AU for the Earth, 1.70 $\cdot$ 10$^{-2}$ AU for Venus and 1.66 $\cdot$ 10$^{-2}$ AU for Mars, as defined in section 2): $\bar{i}_{en}$ is the mean entry inclination, $\bar{i}_{en,\text{max}}$ is the mean maximum entry inclination and $\bar{i}_{en,\text{min}}$ is the mean minimum entry inclination over all clones, $\bar{i}_{ex}$ is the mean exit inclination, $\bar{i}_{ex,\text{max}}$ is the mean maximum exit inclination, $\bar{i}_{ex,\text{min}}$ is the mean minimum exit inclination.
of 200 real Hungarias), and the total number of the initial sample (200), considered as representative of the whole family.

The majority of them are Amors, but there is a consistent number of Apollos that stay constantly growing up till even after all the NEAs reach their maximum value (in fact after the peak of the NEAs, the Amors decrease their quantity). Same behaviour, as for the Apollos, is visible for Atens and IEOs; but after 90 My their number go down, because of impacts (with the planets or with the Sun).
The average life and the relative release of NEA-types in comparison with some results of Bottke et al. [1] is described in Table 11.

Bottke et al. [1] subdivided the source of NEOs (Near-Earth objects, so not only asteroids, but also comets with $q < 1.3$ AU) in different regions (Bottke et al. [1] used the so called extended target region with these constraints: $q < 1.3$ AU, $a < 4.2$ AU, $e < 1.0$, $i < 90^\circ$ and $13 < H < 22$), where we have added the prefix Neas:

- $Neas(v_6)$, where the secular resonance $v_6$ (which occurs when the mean precession rates of the longitudes of perihelia of the asteroid and of Saturn are equal to each other) is more active in the Main Belt.

- $Neas(J3:1)$, where the mean motion resonance with Jupiter $J3:1$ is more active in the Main Belt.

- $NeasIMCs$, Intermediate source Mars-crossing asteroids, the subset of the Mars-crossing asteroid population that borders the Main Belt.

- $Neas(OB)$, the Outer Main Belt.

- $Neas(ECOMs)$, the Ecliptic comets.

We find that the average life of the Hungaria-NEAs (Table 11, where last five rows are referred to Bottke et al. [1]'s regions) is about the double of the asteroid coming from the Outer Main Belt, but much more less then the ones coming from the J3:1 and the $v6$ resonances (see also Table 3 of Bottke et al. [1]). Looking at the average life time spent in a region, they are the majorities of their life Atens during 100 My of integration, but the maximum life is when they are Apollos.
The majority of the fugitives that becomes NEAs are Amors, then IEOs and Atens are moreless in equal number as population of Hungaria-NEAs. The percentage for estimating the population is the normalized number of asteroids per each time ($N$, described before) in percentage, simply $\% = N \times 100$.

Instead, concerning their relative lost of asteroids in the Main Belt, its supply is quite comparable to the Outer Main Belt Region, but more than 2 times less the IMCs (see Table 11). If the lost of these family is constant, in case of no external supply, it will finish its own existence in about 3.125 Gy.

4.2. Impacts

During the integration we found some tens of impacts with the terrestrial planets, Venus captures the highest number (Fig 2 and Table 13). The highest rate of impacts is between 20 and 30 My, but this does not affect the behaviour of increasing the number of NEAs during this interval of time (see Fig 1). Then there is a time span of circa 20 My without impacts with planets (but only with the Sun), starting again in the last 30 My. Other objects that finish may have an impact with Jupiter too, but we did not take in account the study of close encounters with this planet in this work and usually we see a not significant value of asteroids that cross the Jupiter’s orbit. So the most important bodies in cleaning up the Hungarias-NEAs seems to be in order the Sun and Venus. It is important to notice that there is a certain probability (even if it is very small) that Hungarias may hit the Earth and Mars too, that it is important for nowadays studies: the probability for these fugitives to hit the Earth and Mars in 100 my respectively is 0.7% and 1.1%. Comparing the Hungarias to other sources in respect to the impacts with Venus and Earth, the ratio suggests that Hungarias hit more Venus than the others about 3 times more (see Table 12), even if the statics is minimal and the quan-
Table 11: $< L_{TR-100} >$ (My) is the mean life time spent in the target region ($q < 1.3$ AU), and $L_{TR-100, MAX}$ is its maximum value, both during an orbital evolution of 100 My. % is the percentage of Hungarias (the fraction of the total population of the Hungarias, assumed as the first 200 considered as the sample of the whole family, that enter in the target region) which is source of the relative target region in 100 My. Data that are not about Hungarias (H) comes from [1] (see Table 3 and Table 1: i.e. for $\nu_6$, initial number or particles were 3519 and 360 of them became NEO on average, so 10.2 %) and are put only as comparisons; here $< L_{ETR} >$ (My) and $L_{ETR,MAX}$ as the same meaning as previously said with the only different that the value are taken in the extended target region used by Bottke et al. [1] and the objects were integrated there for at least 100 My.
Figure 2: Evolution of the Hungaria-NEAs: time versus number of impacts and their types. The impacts with the Sun are more determinant for the final life of the asteroids: the number of impact with the Sun is always major than the number of the impacts with all the planets, even if the impacts with Venus are comparable especially in the first 20 My.

The impact-rate is very lower with the average of the planetary crossers, making a comparison with Ivanov et al. [10], which take in account the observed planetary crossers with $H < 17$, this is clear in Table 13, the highest contribution by the Hungarias to the impactor populations is $< 3\%$. Between the impactor population the one in which the Hungarias most contribute is the Martian impactor.
Impact flux ratio $H_\nu^6:1 IMC OMB$

| Planet       | $H$  | $\nu_6$ | 3 : 1 | IMC | OMB |
|--------------|------|---------|-------|-----|-----|
| Venus/Earth  | 3.16 | 1.22    | 1.19  | 1.10| 0.77|
| Mars/Earth   | 0.43 | -       | -     | -   | -   |

Table 12: Impact flux ratios (per unit surface area of target), IFR, for Venus/Earth for the individual asteroidal source integrations compared to values in Table 4 of Greenstreet et al. [8].

| Planet | Hungarias $\langle H < 17 \rangle$ | Asteroids ($H < 17$) | % ratio |
|--------|-----------------------------------|----------------------|---------|
| Venus  | 0.014                             | 4.500                | 0.3%    |
| Earth  | 0.004                             | 3.400                | 0.12%   |
| Mars   | 0.006                             | 0.210                | 2.86%   |

Table 13: Average collision probability per one body (planetary crosser) per Gy. The value of the asteroids with $H < 17$ is from Ivanov et al. [10]. % ratio is the ratio in percentage between the rate of impacts in 1 Gy between the 2 tested populations.

4.3. Averaging the elements and analysis

We averaged all the elements of the 50 clones for each fugitives every 1000 years time step. We subdivided the clones in two groups: (1) asteroids that become NEAs ($H_{Neas}$) and (2) asteroids that do not become NEAs ($H_{NoNeas}$).

Finally we consider the data of the group $H_{Neas}$ from the time instant when they start to be NEAs to 10 My after: putting time 0 at the moment when they become NEAs, we do the averaging for the following 10 My (so we average all the Hungaria-NEAs, the clones of the fugitives which are NEAs) and we call this
one \textit{NormHNeas} from now on. For all these cases we will show in detail the averaging over 2 fugitives only, representative for the others 9 ones.

In the case of \textit{HNeas} we see (Fig. 3 and 5) that their semi-major axis oscillates much more than \textit{HNoNeas}, especially after the majorities of them become NEAs and they only decrease this value; instead for the \textit{HNoNeas}, the stability is visible (semi-major axis and eccentricity are almost constant) till arriving in the proximity of the end of the integration. At the end of evolution, in the last $\sim 30$ millions year of integration, the scattering increase visibly, due to some impacts and close encounters with Mars, too.

The eccentricity for the \textit{HNeas} have an average increase of about $0.002 \, \text{My}^{-1}$.

The big scattering visible in Fig. 3 and 5 at $\sim 88$ My for (211279) 2002 RN$_{137}$ and at 65 My for (152648) 1997 UL$_{20}$, is due to some fugitives that escaped immediately out as Centaur or TNO; the same is for some bigger oscillations where the scattering is even higher.

The asteroids that do not become NEAs show such a peak in the scattering because they are a small number in comparison to the ones that become fugitives.

The \textit{NormHNeas} initially decreases their semi-major axis more than 0.05 AU (as a whole) in the first million years and then after this negative gradient, the decreasing of the semi-major axis stops.

Instead the eccentricity after a couple of million years, in the cases where the most unstable clones have important close encounters or even impacts, starts to steadily increase, but below the value of the \textit{HNeas}.

It is relavant a certain big scattering just when they start to be NEAs. Then some fugitives escaped immediately out as Centaur or TNO, or have some impact and the behaviour become more homogeneous (less scattering).
Figure 3: Averaging of the elements with the standard deviation of the 50 clones of the asteroid (211279) 2002 RN137. All points with a standard deviation major than 50% of the measure of the average has been rejected. Left pannel: Semi-major axis versus time for the averaging. The first vertical line is the time when the first clone become a NEA. The second one is the average time for the clones to become NEAs. Right pannel: Eccentricity versus time.

Figure 4: Averaging of the elements with the standard deviation of the 50 clones of the asteroid (152648) 1997 UL20. All points with a standard deviation major than 50% of the measure of the average has been rejected. Left pannel: Semi-major axis versus time for the averaging, at ~ 58 My there is a large scattering. The first vertical line is the time when the first clone become a NEA. The second one is the average time for the clone to become NEAs. Right pannel: Eccentricity versus time.
Figure 5: Averaging of the elements with the standard deviation of the 50 clones of the asteroid (211279) 2002 RN137 when they are NEAs. All points with a standard deviation major than 50% of the measure of the average has been rejected. Left pannel: Semi-major axis versus time for the averaging. Right pannel: Eccentricity versus time.

The analysis on the inclination presents strong scattering giving the studying no possible interpretations.

5. Conclusions

As main result of our integration we found that the preponderance of the Hungaria escapers become NEAs, so also Mars-crossers. 78% has CE with Mars, 29% with the Earth and 24% with Venus. Also 37% finish their lives as Sun-grazers, if they do not collide with a planet before that.

There is a small number of them (with a very low probability: < 1%) that leave the inner main belt crossing the region of the Centaurs and Trans-Neptunian Objects (TNOs).

Some Hungarias pass a long time in the outer solar system, via comet-like orbits, because we observed very high eccentricities when they are NEAs and even at higher inclinations than the initial conditions.
The average time for a first close encounter with Venus is \( \sim 63 \) My after the initial conditions, but it is somewhat surprising that this time is not much smaller for the Earth \( \sim 62 \) My; the first CE with Mars the average time is lower \( \sim 14 \) My. They become NEAs on average after \( \sim 47 \) My.

In the case of Hungaria-derived Apollos or Amors, the Earth is flattening the orbits of the asteroids (decreasing the inclination) close to the ecliptic, which is a well known phenomenon.

These asteroids tend to reducing their heliocentric distances, apart some cases that get into a hyperbolic orbit (this happens with the narrowest close encounters with Mars after they begin to be Mars-crossers), and some have impacts with the Sun, also after only \( \sim 10 \) My of integration, but the majorities of them after 30 My, where the \( \nu_6 \) secular resonance plays an important role.

During their evolution some escapers end their life with an impact, mostly with the Sun and the rest with the planets, in particular the terrestrial planets: the probability for these fugitives to hit the Earth and Mars in 100 My is respectively 0.7% and 1.1%. The highest one is for Venus, 2.5%.

We underline that the majority of the Hungaria escapers change their type-membership when they are NEAs, as it has been discussed in detail also by Milani et al. [12], Dvorak & Pilat-Lohinger [3], and Dvorak & Freistetter [4] and we found that they have a mean life time equal to 0.27 My on average and their relative probabilities to be source of NEAs in 100 My is about 3.2% with 18% of these last ones colliding with the Sun.

The maximum release of NEAs by the escapers is at \( \sim 60 \) My after the initial conditions of the integration; instead if we look at inside the different NEA-types, we found that Atens and Apollos stop to increase at \( \sim 90 \) My. Their average
life-time as NEAs is higher than the one coming from the Outer Main Belt, but
the percentage of relative release is similar; instead this last one is smaller than
sources like the ν6, the $J3 : 1$ and in particular more than 2 times less than the
IMCs. When they are NEAs they pass more time as Atens in 100 My of evolution
after escaping from their proper family. If the lost of these family is constant, in
case of no external supply, it will finish its own existence in about 3.125 Gy.

The majority of the Hungaria fugitives that becomes NEAs are Amors; then
IEOs and Atens are more or less in equal number as population of Hungaria-
NEAs.

Concerning their orbit on average, the semi-major axis continues to decrease,
contrary to the eccentricity that is continuously growing, $\sim 2 \cdot 10^{-3} \text{My}^{-1}$ with
also increasing number of CEs and passing through MMRs with different planets
and some secular resonances. CEs are especially with Mars, also many times just
before being a NEA. We show also that after the Hungarias-NEAs are “cleaned”
by impacts, the remaining ones keep the orbit constant (in semi-major axis and
eccentricity) for an interval time $< 10$ My like the real ones.

About their initial inclination, we think that the former collision started from
a period in which massive bodies (with diameters bigger than at least 30 km) col-
lided inside the Main Belt region, presumably all started with an initial collision
in the inner main belt region for a body with probably high inclination ($i \geq 23^\circ$).
This collision may have given birth to the E-belt [2] and this last one gave origin
to the present Hungarias and a great part of the NEAs.

The fugitives are planet crossing asteroids (PCAs) at least in 91% of the cases
in 100 My, their angles of deflection can be very high – rarely up to more than 90°
(so retrograde orbits, after important CEs), even if on average it is less than 3°.
The duration of their close encounters is maximal for Mars, $\sim 0.5$ days, and minimal for Venus, $\sim 0.25$ days, somewhere in between for the Earth ($\sim 1/3$ days). We could define a relation $2:3:4$ (Venus:Earth:Mars) for the durations of close encounters with terrestrial planets, this is because the encounter velocities of the asteroids are very high for Venus and lower for Mars.

The Hungarias encounter velocities seem to be faster than the average values for the all the real asteroids that come close to the terrestrial planets, especially for the Earth and Venus; for this reason they probably do look like to cause craters bigger then the aver at least less than 3% from the total population of impactors with terrestrial planets, but the most important contribution is toward the population which may impact Mars, $\sim 2.8\%$.

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