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The Hungaria Asteroids: close encounters and impacts with terrestrial planets

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Abstract. The Hungaria asteroid family (Named after (434) Hungaria), which consists of more than 5000 members with semi-major axes between 1.78 and 2.03 AU and have inclinations of the order of 20°, is regarded as one source for Near-Earth Asteroids (NEAs). They are mainly perturbed by Jupiter and Mars, and are ejected because of mean motion and secular resonances with these planets and then become Mars-crossers; later they may even cross the orbits of Earth and Venus. We are interested to analyze the close encounters and possible impacts with these planets. For 200 selected 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 to only gravitational forces. We picked out a sample of 11 objects (each with 50 clones) with large variations in semi-major axis and some of them achieve high inclinations and eccentricities in connection with mean motion and secular resonances which then leads to relatively high velocity impacts on Venus, Earth and Mars. We report all close encounters and impacts with the terrestrial planets and statistically determine the mean life and the orbital distribution of the NEAs of these Hungarias.

Key words. Hungarias – asteroids – close encounters – impacts – NEAs – terrestrial planets

1. Introduction

The Hungaria group contains about 8000 asteroids, located in orbital element space [1] between $1.78 < a(AU) < 2.03$, $e < 0.19$ and $12° < i < 31°$, inside the ν_6 secular resonance (SR) and the mean motion resonances (MMRs) 4:1 with Jupiter (J4:1) and 3:4 with Mars (M3:4).

There is evidence from meteorites that members of the Hungaria group may reach the terrestrial planets and be a source of impactors. In the first place this is deduced from the spectral type of the major component of the family, the E-type or Achondritic Enstatite (about 60%) , which is consistent with the composition of some meteorites (aubrites, Zellner et al. (1977) found on the Earth. Other Hungarias are also S-type (17.2%) and less C-types (6.0%) (Warner et al. 2009). The objects of the group are not very big in size compared to the other Main Belt Asteroids (MBAs), they have an average diameter of 1 km ranging up to 11.4 km, (434)Hungaria being the biggest member. The majority of Hungarias have a retrograde rotation and similar spin rates (Pravec et al. 2008; Rossi et al. 2009).

[1] following in part a suggestion of Spratt (1990), so that our sample finally consisted of 8258 asteroids (August 2010)

The content of the paper is as follows:

- methods and details on the investigated bodies;
- statistical and analytical study on Hungarias path to be NEAs, impacts and close encounters with the Terrestrial planets;
- conclusions: discussion and summary on the previous described studies.

2. Methods and details

Hungaria asteroids was picked up from the database[2] of the Lowell observatory at Flagstaff, then a reasonable number of asteroids was taken for the orbital integrations: 200 out of the total Hungarias inside the group, the ones that have the higher deflection from the average of a metric d based on the osculating elements: $d = \left|\sqrt{(\frac{e}{<e>})^2 + (\frac{a}{<a>})^2 + (\frac{\sin i}{<\sin i>})^2}\right|$ (a, e and i are respectively the semi-major axis, the eccentricity and the inclination of the asteroids).

Firstly these first sample was integrated for 100 My with the Lie-integrator (Hanslmeier & Dvorak 1984; Eggl & Dvorak 2010) in a simplified Solar system (planets from Mars to Saturn), enough[3] for the scope of this first work, discovering the objects which escape from the group: 11 bodies (see Table 1). They were discriminated considering only those ones who has a major deflection in the semi-major axis: $\Delta a > \Delta a_{group}/16 = 0.01563$ AU, with $\Delta a = a_{max} - a_{min}$: deviations from the group's mean semi-major axis of more than $\sim 7\%$ of the total width of the group.

Secondly the 11 fugitives were integrated again with the same initial conditions and together with 49 clones for each one of them inside these ranges: $a \pm 0.005$ AU, $e \pm 0.003$ and $i \pm 0.005°$. This time in a Solar System which take in accounts all the planets from Venus to Saturn, so taking in account also the terrestrial planets and all the close encounters. It is considered a close encounter when the asteroid crosses the following distances (close encounter radius, CER) from each planet: the average lunar distance 0.0025 AU for the Earth, and the lunar distances scaled to the respective Hill Sphere of the other 2 considered planets 0.00166 AU for Mars and 0.00170 AU for Venus.

2 www2.lowell.edu/elgb

3 Integrations with the full Solar System from Mercury to Neptune shows the same general results.

3. Results

3.1. Statistical analysis of the dynamics of the Hungarias' Fugitives.

The 11 fugitives are also inside the Hungaria Family, so it is possible to speak about escapers from the family, a more restrictive definition of "group"; we remember here the definitions:

Group: a "group" of asteroids is defined by a range of osculating elements (see also Warner et al. 2009)

Family: a (dynamical) "family" of asteroids is defined by the use of the proper elements. Families are defined by a specifical clustering method, which gives dynamically a homogeneous sample of asteroid in the Main Belt, the most well known are the Hierarchical Clustering Method (HCM, Zappalá et al. 1990) and the Wavelet Analysis Method (WAM, Bendjoya et al. 1991).

The orbit of the fugitives is rather chaotic after a close encounter as it can be seen in the case of (41577) 2000 SV_2 (Fig. 2). This asteroid become a Sungrazers in less than 100 Myrs, crossing the ν_6 secular resonance at $\sim 71 Myr$ and then after a very close encounter with Venus, it become a NEAs keeping a high value of eccentricity, always $e > 0.3$, finally after several close encounters with all the planets, it collides the Sun.

During the orbital evolution of 100 Myrs, all the Fugitives become Mars-crossers. 91 % of them (the clones) are planet crossing asteroids (PCAs) and 58% NEAs, in particular Amors and Apollos: Amors are the Earth-approaching NEAs with orbits exterior to the Earth's ($a > 1.0AU$ and $1.017(AU) < q < 1.3(AU)$; Apollos are Earth-crossing NEAs

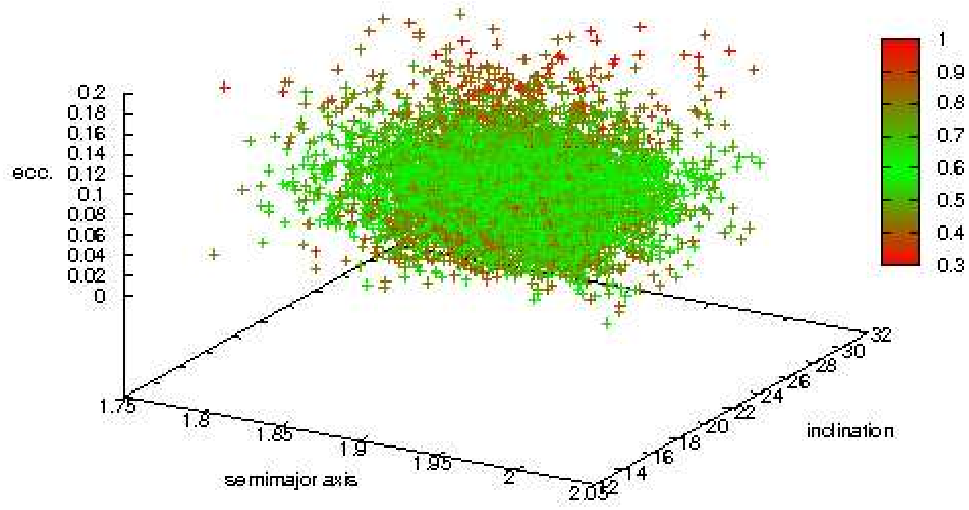

Fig. 1. The Hungaria group in the orbital space and the metric. Reddish crosses are for the asteroids with the most extreme value in the metric.

with semi-major axis larger than the Earth ($a >$ 1.0 AU and $q <$ 1.017 AU, q is the perihelium), this means that 3.2% of all the Hungarias become NEAs in 100 Myrs. The average time-evolution of the Hungarias escapers is shown in Fig. 3, a Fugitive usually have a close encounter with Earth and Venus after becoming an Amor, an Apollo and an Aten.

The entry velocity at the *CER* for each planet it is 21.5 ± 2.3 km/s for the Earth, 27.8 ± 1.7 km/s for Venus and 10.8 ± 1.0 km/s for Mars.

3.2. Impacts

Some singular clones have an impact with a terrestrial planet. The percentage of the whole Hungaria's population having an impact with a terrestrial planet during 100 Myrs is: 0.7% for the Earth, 2.4% for Venus and 1.1% for Mars. It is possible to compute the diameter of the putative craters and some typical values concerning them. In order to make this the diameter of the asteroids is needed, see (Table 1). They are computed with the equation of Fowler & Chillemi (1992), which gives a quite precise results, with an error, usually of second order (if the diameter is 220km the error is about of $20^1 km$, see Galiazzo 2009): $D = \frac{1329}{\sqrt{\rho_v}} 10^{-H/5}$.

The estimates of the diameter of the Hungaria-impactors are based on the assumption that the asteroid has a spherical shape.

The known impact structures on Earth range from small circular bowls only a few hundred metres in diameter to large complex structures more than 200 km in diameter (French 1998), with ages as old as 2 Gyr. The biggest known craters on Earth are Vredefort and Sudbury craters, larger than 200 km in diameter. The "projectiles" capable of forming craters on the terrestrial planets today come primarily from three populations(Ivanov et al. 2002a):

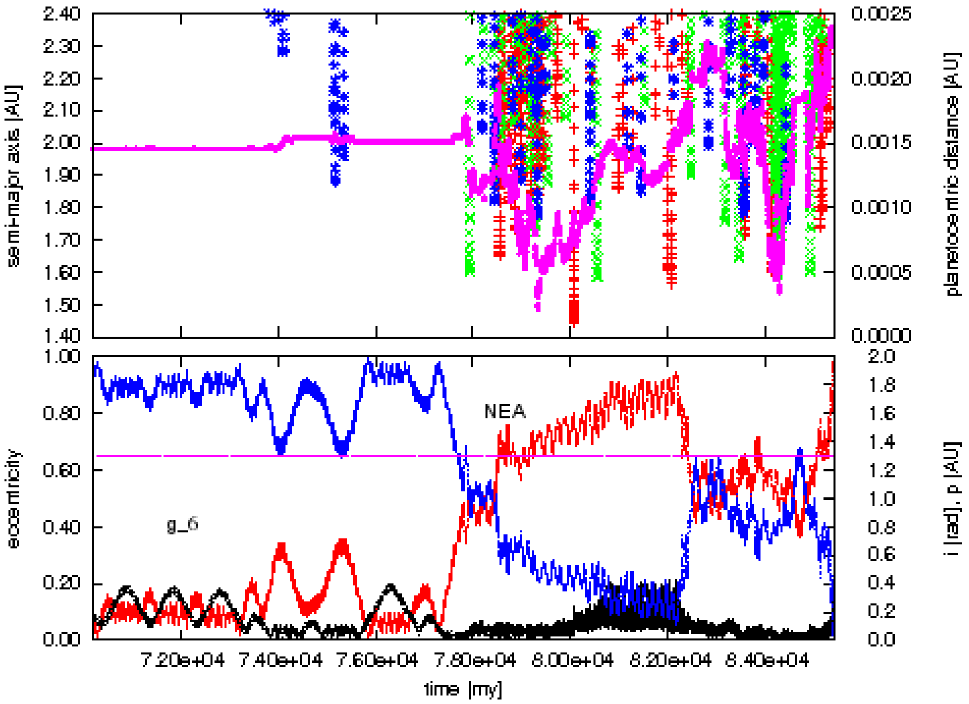

Fig. 2. Upper panel: semi-major axis and Planetocentric distance versus time. In blue, green and red, close encounters with respectively: Mars, Venus and Earth. Bottom panel: eccentricity (red), inclination (black) and perihelium (blue) versus time.

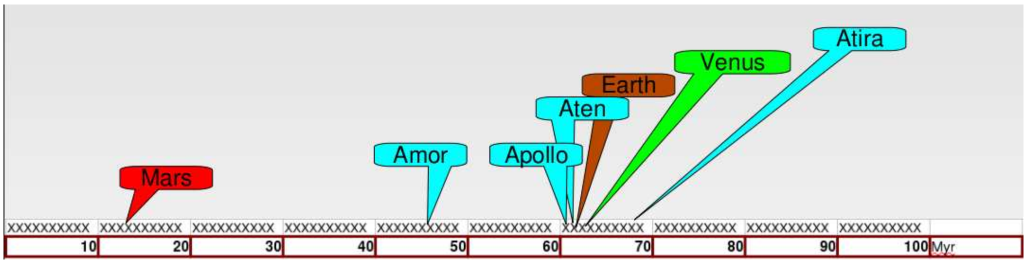

Fig. 3. Average time-evolution of a Fugitive. Each "x" represents 1 Myr. Atens are Earthcrossing NEAs with semimajor axis smaller than the Earth: $a < 1.0$ AU and $Q > 0.983$AU (Q is the aphelion); Atiras have the orbit contained with the one of the Earth: $a < 1.0$ AU and $Q < 0.983$ AU.

1. asteroids from the main belt
2. Jupiter-family comets from the Kuiper Belt
3. long period comets from the Oort Cloud

Bottke et al. (2002) showed that the asteroids provide most of terrestrial impact craters coming from $a < 7.4$ AU orbits. Some hundreds of NEAs have a diameter ≥ 1 km similar to most of the known Hungarias. For the found fugitives the diameters range from approximately 1 km to ~ 2.5 km, see Table 1.

Table 1. Absolute magnitude in visual, slope parameter,diameter (km) and spectra types of the 11 fugitives. Data from the database "astorb.dat" of the Minor Body Center. Where not data are given for the visual albedo (ρ_v), the average (aver.) one, 0.38 (Warner et al. (2009), was taken. Question mark stands for no data available for the spectrum type.

Asteroid	H_V	G	D	ρ_v	Spec.-Type
(211279) 2002 RN_{137}	16.9	0.15	1.01	0.3	Xe?
(41898) 2000 WN_{124}	16.2	0.15	1.24	aver.	?
(39561) 1992 QA	15.3	0.15	1.88	aver.	?
(30935) Davasobel	14.7	0.15	2.48	aver.	S?
(175851) 1999 UF5	16.9	0.15	0.90	aver.	Xe?
(152648) 1997 UL_{20}	15.8	0.15	1.49	aver.	?
(141096) 2001 XB_{48}	16.2	0.15	1.24	aver.	?
(24883) 1996 VG_9	15.3	0.15	1.88	aver.	?
(41577) 2000 SV_2	14.9	0.15	2.26	aver.	?
(129450) 1991 JM	16.8	0.15	0.94	aver.	?
(171621) 2000 CR_{58}	16.2	0.15	1.24	aver.	?

3.3. Craters

During the integrations some clones have an impact with Terrestrial planets. The impact is assumed if the body surmounts the limit for the atmospheric entry (see Fig. 1 of Westman et al. 2003), for this cutoff[4] it has been chosen in this work a value for the Earth equal to 65.4 km. For the other planets it has been derived an empirical equation using a constant k which depends on the scale height h_{atm} of the atmosphere, measured in astronomical units (1 AU = 149597870.7 km) and the (surface) density of each planet (for parameters see Table 1):

$$k = \rho^{(E)} h_{tot}^{(E)} / h_{atm}^{(E)} \tag{1}$$

where

$$h_{tot}^{(E)} = r^{(E)} + h_{atm}^{(E)}. \tag{2}$$

Here $h_{atm}^{(E)}$ is the scale height of the Earth atmosphere, $\rho^{(E)}$ the density, and $r^{(E)}$ is the radius of the Earth (also in astronomical units). The atmospheric entry (r_{imp}) for Venus and Mars is given by the equation:

$$r_{imp} = r^{(P)} + h_{tot}^{(P)} \rho^{(P)} / k. \tag{3}$$

The probabilities computed from the results of the integrations confirm the trend and the values found in Ivanov et al. (2002a) for bodies with $H < 17$ mag, even if the value for Mars is very small compared to the results of this paper (0.21 compared to 0.34). This bias is due to the fact that here it is used a small sample and restricted to a special group of asteroids. Averaging on the fugitives which have impacts (9 out of 11), the average probability range from $(2.20-3.49)\times10^{-8}$/yr, meaning that a fugitive should orbit between 0.026 – 0.045 Gyr at its currently observed orbit before impacting one of the terrestrial planets[5].

The impact angle is defined via the angle of the planetocentric velocity vector with the normal to the target's surface:

$$\cos(\theta_{norm}) = \frac{\boldsymbol{v} \cdot \boldsymbol{n}}{||\boldsymbol{v}|| \cdot ||\boldsymbol{n}||} \tag{4}$$

and so $\theta = 90° - \theta_{norm}$. The diameter of the crater by means of the equations for the transient crater diameter (Collins et al. 2005):

$$D_{tc} = 1.161 \left(\frac{\rho_i}{\rho_t}\right)^{1/3} D_i^{0.78}\, v_i^{0.44}\, g^{-0.22}\, (\sin\theta)^{1/3}, \tag{5}$$

here D_i is the diameter of the impactor, ρ_i its density (for the Hungarias we chose ρ_i =

[4] see http://neo.jpl.nasa.gov/news/2008tc3.html

[5] 0.040 Gyr for the Earth, meaning that impacts by Hungarias may happen since ∼ (0.46 – 0.92) Gyr ago. However this is only one of the probable suggestions, so caution may be advised before completely accepting these connections.

Table 2. ρ_1^{Earth} and ρ_2^{Earth} are the densities of sedimentary and crystalline rock, respectively, (Collins et al. 2005); ρ_1^{Venus} is the (surface) densitity given by the fact sheet of NASA (http://nssdc.gsfc.nasa.gov/planetary/factsheet/venusfact.html) and ρ_2^{Venus} is the upper limit of basalt given in http://geology.about.com/cs/rock_types/a/aarockspecgrav.htm. ρ_1^{Mars} is the density for Mars: we have considered the lower value for andesite (see the link mentioned just before). For the scale heights of the atmospheres (h_{atm}) we have chosen for the Earth the value mentioned at http://neo.jpl.nasa.gov/news/948tc3.html. All the other parameters come from the NASA fact-sheets for each planet.

Planet	radius R [km] pressure P [bar]	density ρ_1 $[kg/m^3]$ h_{atm} [km]	density ρ_2 $[kg/m^3]$ g $[m/s]$
Venus	6051.8	2800	3000
	92	15.9	8.9
Earth	6371.0	2500	2750
	1.01325	8.5	9.8
Mars	3396.2	2500	–
	0.00636	11.11	3.71

1700 kg/m^3, McEachern et al. 2010), and ρ_t is the density of the target. For the final crater diameter (McKinnon & Schenk 1985) it follows:

$$D_c = 1.17\, \frac{D_{tc}^{1.13}}{D_*^{0.13}}, \tag{6}$$

with D_* the transition diameter inversely proportional to the surface gravity of the target (Melosh 1989), with the nominal value for the Moon of $D_{*,Moon} = 18$ km (Minton & Malhotra 2010):

$$D_* = 1.62\, D_{*,Moon}/g^{(P)}. \tag{7}$$

Earth: Grieve & Shoemaker (1994) suggest that it is possible to distinguish two populations of craters: (i) craters with diameters between 24 to 39 km, the oldest being 115 Myr; and (ii) craters with diameters from 55 to 100 km, the oldest being 370 Myr. Ivanov et al. (2002a) assume that craters smaller than ~ 20 km belong to the younger set, so Hungarias should have formed craters younger than 115 Myr. This should be compared to the diameters found from our computations (see Tables 3,4 and 5), with the biggest crater formed by 2002 SV2 (20.89 km).

Mars: In the equatorial geologic-geomorphic units of Mars (latitude $\leq 35°$), there are craters that range from 4 to 10 km (Condit 1978), similar to the putative crater made by a clone of 1996 VG9.

Venus: Looking at the Venus database[6], also here a lot of craters has similar diameters to the ones found in these studies.

The impact energy, is computed via the equation given by Collins et al. (2005):

$$E = \frac{\pi}{12}\rho_{ast} D_{ast}^3 v_i^2 \tag{8}$$

This is the energy equivalent in megatons (Mt) if we consider the impactor's diameter D_{ast} expressed in meters, its velocity v_i in km/s and the density ρ_i in g/cm^3. As can be seen the energy depends strongly on the diameter of the impactor and on the impact velocity, which is computed by the equation given in Collins et al. (2005):

$$v_i = v_\infty\, \frac{\rho_i D_i}{\rho_i D_i + \frac{3\,P_{pl}}{2\,g_{pl}\sin\theta}}. \tag{9}$$

(using v_∞ as the speed of the asteroid before the atmospheric entry, D_i impactor diameter, P_{pl} atmospheric pressure). The maximum impact energy released for the Earth is $\approx 4.18 \times 10^5$ Mt, more than forty thousand times the energy

[6] http://www.lpi.usra.edu/resources/vc/vcnames/

released to create the Meteor Crater in Arizona, USA (Shoemaker 1983). The impact energies for Venus are on average lower than on Mars.

Tables 3, 4 and 5 summarize the data for the impacting asteroids, including the energy released by the "crash" of the impactor and the diameter of the crater[7] on the two main types of the solid surfaces of the Earth (sedimentary rocks and crystalline rocks); two different surfaces for Venus (strong andesite and strong basalt), and one for Mars (andesite).
For each planet they are shown the maximum crater diameter made by the fugitives and the real craters on the terrestrial planets with similar diameter to the one made by the Hungarias. D_1 and D_2 are the crater diameters for a sedimentary surface (the bigger one) and for crystalline surface, for the Earth; strong andesite surface (the bigger diameter) and strong basaltic surface for Venus, and only feeble andesite surface for Mars. θ is the angle of impact; E, the energy released by the impact and $E_{Nord.Cr.}$ displays how many times we have the energy of the Nördlingen crater (the energy released by the impactor in the Ries Crater is $\sim$ 15 megatons, see the impact database of the Planetary Space Science Centre), a thousand times the energy released at Hiroshima (15 kilotons, see http://www.world-nuclear.org/info/inf52.html) compared to the energy released by the Hungaria escapers. Then v_∞ is the velocity at the atmospheric entry, v_{imp}, the impact velocity and v_e is the relative escape velocity of the planet. There are also the orbital elements (a, e, i) at the border distance to be considered as a close encounter; the time of the impact t from the beginning of the integration and the disclosure time to arrive from the lunar distance to the target (to the limit of the atmospheric entry), Δt.

Asteroid (152648) 1997 UL_{20} have the maximum number of impacts by its clones, 11 different ones.

[7] All the diameters refer to an asteroid that does not suffer from fragmentation during its flight through the atmosphere.

The inclination at the atmospheric entry looks very high for Mars and contrary for the Earth, while the eccentricities continue to increase going interiorly the solar system. The average impact angle seems higher for the Earth and also the biggest craters appear here.

The impact velocity of the fugitives found for the Earth range from 14.2 to 30.18 km/s for the Earth. These values are larger than the results given by Ivanov & Hartmann (2002b); Chyba (1993) ($\langle v \rangle$ = 19.3 km/s for an asteroid with $H_v < 17$ mag and $\langle v \rangle$ = 18.6 km/s for $H_v < 15$ mag), even if that sample is for asteroids with $D < 50$ m. Hungarias seem to arrive faster on the average than other types of asteroids having close encounters with the Earth. Concerning Mars the range of velocities is from 9.32 to 23.42 km/s with the maximum value higher than for the average asteroids found in Ivanov & Hartmann (2002b), so the Hungarias arrive faster to Mars, too. On the other hand we find lower velocities for Venusian impactors, our results range from 5.24 to 24.57 km/s, against the average velocity of 24.2 km/s of Ivanov & Hartmann (2002b).

Some NEOs (in the JPL Small-Body Database Search Engine) fit well with the elements of the found impactors, also inside the ranges of the albedos and absolute magnitudes of the Hungarias, spectra types gave a good fitting, when they are present: (1620) Geographos, (2201) Oliato, (5751) Zao, (3551) Verenia, (5604) 1992 FE, an Amor asteroid of 2.3km (Delbó et al. 2003).

4. Conclusions

In 100 Myrs, 3.2% of all the Hungarias become NEAs and among these more than 90% are PCAs. Less than 1 % of them has an impact with Mars or the Earth, 2.4% of them with Venus and the rest end up as a Sun-grazer or stay still in a NEA's orbit; very rarely they are Jupiter crossers.

Found Hungaria fugitives which collide a planet create craters similar to the ones present on the terrestrial planets as dimension ($D < 30km$). The biggest computed craters for them are 28 km for the Earth, 20 km for Venus and 23 km for Mars.

Table 3. Earth-impacts

Asteroid Energy [Mt $\times 10^5$] semi-major axis [AU]	D_1 [km] $E_{Nord.Cr.}$ eccentricity	D_2[km] v_∞ [km/s] inclination [deg]	θ v_{imp} [km/s] time [Myr]	 v_e [km/s] Δt [h]
Earth craters				
Davasobel	27.47	26.61	55	
4.181	15.48	15.23	16.05	11.20
0.8020	0.3918	6.10	89.182	9.5
Crater	Diameter[8]	v_{imp}[9]	Age[10] [Ma]	
Slate Islands	30.00	~ 20km/s	436	–

Table 4. Venus-impacts.

Venus craters				
2000 SV2	19.60	19.15	43	
4.851	17.965	31.21	19.88	10.2
0.9269	0.3755	46.47	97.403	3.87
Crater	Diameter[11]	v_{imp}	Age [Ma]	
Rowena	19.6	–	–	–

Table 5. Mars-impacts.

Mars craters				
2000 SV2	22.85		53	
2.689	9.958	14.57	14.80	5
Crater	Diameter[12]	v_{imp}	Age [Ma]	
Endeavour	22.0	–	–	–

Some NEOs presents similar osculatory elements, size and spectral type (when it is available) to the fictitious fugitive-impactors: (1620) Geographos , (2201) Oliato, (5751) Zao, (3551) Verenia, (5604) 1992 FE.

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