Univerzita Komenského v Bratislave

Fakulta matematiky, fyziky a informatiky

Meno a priezvisko

Eva Schunová

Autoreferát dizertačnej práce

Komplexy malých telies slnečnej sústavy: rodiny blízkozemských asteroidov

na získanie akademického titulu philosophiae doctor

v odbore doktorandského štúdia:

4.1.7.-8. Astronómia a astrofyzika

Miesto a dátum:

Bratislava, 2012

(**2. strana autoreferátu**)

Dizertačná práca bola vypracovaná
(v dennej forme doktorandského štúdia)

na (Fakulta matematiky, fyziky a informatiky, Univerzita Komenského v Bratislave)

Predkladateľ: **Mgr. Eva Schunová**
Univerzita Komenského v Bratislave
Fakulta matematiky, fyziky a informatiky
Oddelenie astronómie, fyziky Zeme a meteorológie

Školiteľ: **prof. RNDr. Vladimír Porubčan, DrSc**
Univerzita Komenského v Bratislave
Fakulta matematiky, fyziky a informatiky
Oddelenie astronómie, fyziky Zeme a meteorológie

Oponenti: ....
....
....
....
....
....
(meno a priezvisko oponenta s uvedením jeho titulov a hodností
a názov ustanovizne, s ktorou je oponent v pracovnom pomere)

Obhajoba dizertačnej práce sa koná .... o .... h
pred komisiou pre obhajobu dizertačnej práce v odbore doktorandského štúdia vymenovanou predsedom odborovej komisie ....
(uviesť dátum vymenovania)

4.1.7 – 8 Astronómia a astrofyzika
(študijný odbor) (názov študijného programu doktorandského štúdia)

na
Univerzita Komenského v Bratislave
Fakulta matematiky, fyziky a informatiky, Oddelenie astronómie, fyziky Zeme a meteorológie
Mlynská dolina
84248 Bratislava

Predseda odborovej komisie:
doc. RNDr. Jozef Klačka, CSc.
Univerzita Komenského v Bratislave
Fakulta matematiky, fyzikya informatiky
Oddelenie astronómie, fyziky Zeme a meteorológie

Table of contents

Motivation

Groupings of main belt asteroids with common origin called families have been known since 1918. Their identification is based on the similarity of orbital elements and spectral features of actual family members. It is somewhat surprising given the large number of confirmed main belt families, that no such association has been observed among near-Earth object (NEO) population so far, despite the rapid discovery rate of new NEOs.

The goal of this work is to analyze the origin, evolution, lifetime and detectability of families in the NEO population, and using the results of the theoretical approach in search for real families.

In the first part of this work we inspect several of their possible creation scenarios, and primarily focus on the families created by tidal disruptions during a close encounter with terrestrial planets. We assess the disruption likelihood with all terrestrial planets, and by performing disruption simulations of selected NEOs near Earth and Mars we create number of synthetic families. We closely inspect the pre- and post-encounter conditions and physical features of resulting families. We asses their lifetime and detectability, frequency of occurrence and also the collisional probability with terrestrial planets by inspecting the dynamical evolution of their members, resulting from performed numerical integrations up to 1 Myr after disruption.

In the second part of our work we use our results in search for clusters of NEOs in the real population, followed by assessment the statistical significance, with help of 1000 NEO model we have developed for this purpose.

The final part of the second section is dedicated to the analysis of the possible origin, age, orbital evolution and physical properties of 3 statistically most significant clusters found in the real population, which are the high candidates for a first NEO family.

1. Introduction

Hirayama (1918) was first to suggest that asteroids in the main belt (MB) with very similar orbits could have a common origin. They form groupings called families, which are the remnants of large parent objects and also the evidence of ancient powerful collisions between asteroids. More than 50 collisional asteroid families are known up to date, residing in the main belt (Hirayama 1918, Nesvorný et al. 2005, Nesvorný et al. 2006). Orbits of main belt asteroids (MBAs) are stable on timescales comparable with the age of solar system, which allows us to detect families with age up to several billions of years. The identification of the main belt families is based on the similarity of proper elements of actual family members, namely on a_p, i_p and e_p, which are the average values of semi-major axis, eccentricity and inclination over a large timescale (Knežević et al. 2002). Several works (Cellino et al. 2002, Izvezić et al. 2002) based on spectroscopic campaigns independently confirmed common origin of families‘ members, as the asteroids belonging to one family usually belong to the same taxonomic class.

Subsequently as the family grows older, multiple effects, such as secondary collisions, gravitational perturbations, close encounters with other larger asteroids and semi-major axis change due to the radiation effects like YORP and Yarkovsky[1] (Bottke et al. 2001) are acting on it's members and a gradual dissipation of fragments in the orbital element space can be observed. The dissipation allows the evolution of families to be traced, and also age determined by backward integrations of their orbits. In the time of origin heliocentric orbits of family members should match.

No genetically related groupings of objects have been identified among the NEO population so far, despite several attempts (e.g. Drummond 2000, Fu et al. 2005). This is most likely is the result of several aspects in which main belt an near-Earth population differ. Firstly, Near-Earth objects were formed and reside in significantly different dynamical environment than MBAs. NEO population is rather transient, being constantly depleted and replenished by fresh objects from different sources, in terms of dynamics and also composition. The average lifetime of NEOs is only roughly 10^6 years (Morbidelli et al. 2002, Gladman et al 1997) under the strong gravitational influence of planets. Calculating proper elements for NEOs is for this reason very complicated, but not impossible (Groncchi et al. 2001). Due to this compications, all authors who attempted to search for NEO families used osculating elements instead.

The major disadvantage which lowers the chance of finding a NEO family, is its detectability over much shorter timescales than in the main belt region, using methods based on comparing orbital similarity. Fragments of a NEO family will dissipate into the background very fast due to the chaotic nature of orbits in the near-Earth region (Fu et al. 2005). Thus it is reasonable to expect, that a hypothetical NEO family would only be possible to detect during a very short time comparing to several millions of old MB families.

Secondly, the density of NEO population is low comparing to MBAs (Walsh et al 2008) and the largest NEOs are an order of magnitude smaller the average size of MBAs. Therefore the actual family members would be rather faint and difficult to discover. In addition, there is a general lack of spectroscopic and photometric data for NEOs, which makes the search for NEO families according to their spectral type similar to MBA surveys (Cellino et al. 2002, Izvezić et al. 2002) rather difficult.

In contrary to MBAs collisions are less likely to happen in the NEO population, and creation of a collisional family must be rather rare event. Therefor NEO families must have

---

[1] Yarkovsky effect, diurnal and annual, is caused by anisotropic radiation of absorbed sunlight from the rotating object's surface. It causes an semi-major axis drift on timescales of 10^5 -10^6 years. YORP (Yarkovsky-O'Keefe-Radzievskii-Paddack) is a special cause of Yarkovsky effect, which leads to change of the rotational rate of an asteroid. Both effects are functions of size, shape, spin and material properties (Bottke et al. 2001).

also another creation mechanisms. Among the most likely NEO-family producing events might be:

1. a MBA collision producing a family near a resonance followed by rapid dynamical evolution of some of the members into NEO orbit
2. intra-NEO collisions
3. NEO-MBA collisions
4. tidal disruption of NEOs
5. NEO disruption by rotational fission

Tidal disruption is one of the most probable scenarios for producing a NEO family due to fairly common close encounters of NEOs with terrestrial planets.

When an fragile NEO (rubble-pile) is passing by planet within its Roche limit under certain dynamical conditions, it could be torn apart by acting tidal forces. Several pre-encounter conditions, such as the encounter velocity $\boldsymbol{v}_\infty$ and perigee/periapse distance $\boldsymbol{q}$, spin, spin orientation, elongation and spin axis orientation rule the disruption outcome (Richardson et al 1998, Walsh et al 2006). Depending on the conditions, asteroid can split into several fragments of similar mass, into a binary (2 large fargments), sufer only a mild mass loss, or just change shape. Throughout this work we consider only the first scenario as one leading to production of an obserable NEO family. NEO binaries were thoroughly investigated in works of Walsh et al. (2006 & 2008), where they concluded, that tidal disruptions should account only for approximately 1-2% of binary NEOs

In the third case tidal forces are able to small particles from the object’s surface and thus create a meteor stream, as Vereš et al. (2008) had suggested in their work. In a general approach, meteor stream is also a family, only its members are several orders of magnitude smaller than members of asteroid family in traditional understanding. Currently the only commonly accepted example of association of NEO and a meteor stream is the case of an Apollo asteroid (3200) Phaethon, which has an orbit extremely similar to the mean orbit of the Geminid meteor stream (Whipple 1983, Ohtsuka et al. 2008). The orbit of (3200) Phaethon is unusual by its very low perihelion distance q=0.140 AU, but despite the obvious orbital similarity with Geminids it never displayed any cometary activity. It might be a dormant comet, whose activity has ceased only recently.

2. Methods

2.1 Tidal disruption simulations

In the first part of our work we performed large number of numerical simulations mimicking the tidal disruption events of NEOs in the vicinity of Earth and Mars, following the work of Walsh et al. (2006, 2008). Mercury and Venus were excluded from our simulations due to the high encounter velocities of NEOs with this planets (K. Walsh 2012, personal communication), which implies, that a violent tidal disruption necessary for creation of a family with several fragments would be unlikely to happen. Moon was also excluded from simulations, because Richardson et al. (1998) showed, that due to its smaller Roche's radius Moon tends to disrupt significantly fewer rubble piles than Earth. The simulations were performed using parallelized tree code *pkdgrav*, which was developed for N-body gravitational and collisional simulations (Richardson et al. 2005).

Every simulation was performed in planetocentric frame and run for 50,000 timesteps, with timestep 10^{-6} yr/2π. Duration of every simulation was then 2.9065 days. The rubble pile model consisted of solely gravitationally-bound identical rigid spheres. Each spherical progenitor consisted of roughly 2,000 particles, which represented the building blocks of rubble piles, ~60 m in diameter. The bulk density of resulting tightly-packed spherical progenitors was ~ 2.1 g.cm^{-3}, with diameters up to ~3.3 km. All progenitors were spherical objects with prograde rotation period P = 4.3 hours.

We have chosen a flat *(a e i)* - distribution for the initial pre-encouter orbits of parent bodies. The advantage of such setting is it's flexibility - later the results could be normalized to match any chosen NEO model orbital distribution. Two sets of 10,000 initial orbits were created, first containing Earth-, the second Mars-approaching orbits. Then a subset of orbits with the most-disruption favourable $\boldsymbol{q}$ and $\boldsymbol{v}_\infty$. was selected as an input for disruption simulations. From all disruption events that occurred in both sets of runs we selected for further analysis those, where disruption produced N > 2 fragments.

2.2 Numerical integrations and identification of NEO families

As a next step the orbits of resulting fragments of each successful disruption at the end of disruption were converted to heliocentric coordinates and numerically integrated forward. The end-epoch of the simulation was set as the zero-epoch of each integration. Members of all families were integrated up to 10^6 years into the future in order to inspect their orbital evolution after the disruption. All integrations were done by N-body Bulirsch-Stoer algorithm with variable timestep from the software package *Mercury6* (Chambers et al. 1999). Every family was integrated separately on the *neohq1* cluster located at the Institute for Astronomy University of Hawaii in Honolulu. The total time of integration was four weeks.

From the integration output we selected the orbits of every fragment in a certain epoch, and by applying our cluster detection method we were searching for members of each family in order to assess the lifetime of NEO families. We adopted the cluster identification method developed by Fu et al. (2005) for the purpose of identifying families in the various stages of their evolution. The method is based on the evaluation of the orbital similarity with Southworth-Hawkins D-criterion - D_{SH} (Southworth and Hawkins, 1963). It uses two D_{SH} threshold values, denoted as D_c and D_p in search for clusters and pairs and strings of pairs in the set of orbits, where $D_c > D_p$. The identification of every cluster is based on the values of 4 parameters: D_c - the maximum D_{SH} between any pair of objects in a cluster, D_p - the maximum D_{SH} between `tight' pairs in the cluster (core of the cluster), SCR_{min} - the maximum String length to Cluster size Ratio, and PF_{min} - the minimum fraction of pairs of asteroids in the cluster with D_{SH} < Dp.

The candidate clusters are identified as sets of N objects with mutual D_{SH} < Dc. Then, within each candidate cluster all pairs (n) of asteroids with D_{SH} < Dp are identified, and also string length (L), the maximum number of objects that are connected in a continuous pair-wise fashion such that each sequential pair in the string satisfies D_{SH} < Dp, is determined.

Every cluster have to satisfy two conditions. First is such, that PF > PF_{min} where the pair fraction PF is the number of detected pairs (n) divided by the number of all possible pairs in the cluster: $PF = \frac{n}{N(N-1)/2}$. The second condition to be satisfied is SCR>SCR_{min}. The SCR is then the ratio of the number of objects in the string to the number of objects in the cluster, SCR=L/N. The PF and SCR cuts recognize that as NEOs undergo rapid dynamical and non-gravitational evolution some of the members may evolve quickly onto different orbits. The pair and string searches therefore allow for a tight `core' of objects with a periphery of other objects.

2.3 Searching for NEO families in the real population

We have searched for families in the NEO population using the method proposed by (Fu et al. 2005). The technique allows for and favors sub-clustering within the cluster under the assumption that there could be a tight `core' within a family (cluster) surrounded by a looser assemblage of related objects. We limited our search for families with use of the NEO osculating elements from *mpcorb.dat*[2]. This only allows us to identify NEO families that are very young.

Due to the various formation scenarios we can expect that there could be some NEO families containing only a handful of objects. In order to find them we have selected the values of four threshold parameters (D_c, D_p, SCR_{min}, PF_{min}). We performed a cluster search on the realistic synthetic NEO model in order was to find such a combination, or combinations of SCR_{min} and PF_{min} for which no clusters would be detected. Values chosen this way maximized the cluster detection efficiency in the real NEO population, while minimizing the contamination by false positives, because in the synthetic model all detected clusters would be false. This investigation also revealet, that it is basically impossible to assess the statistical significance of real NEO triplets. Therefore we later used chosen SCR_{min} and PF_{min} to to identify only clusters containing ≥ 4 members in the real population, and indeed we have found three tightly bound NEO clusters.

Because the real difficulty in identifying NEO families is not the identification of the clusters but in establishing their statistical significance. We performed an thorough statistical analysis. We first tested our method on synthetic family-free NEO orbit models but then proceeded to develop realistic family-free NEO orbit models derived from the known NEO population. We used multiple instances of the family-free NEO models to establish the statistical significance of our NEO clusters, using the full range of tighter thresholds on the D_c and D_p values.

3. Results

3.1 NEO families created by tidal disruption

[2] Orbital database maintained by The minor planet center: http://www.minorplanetcenter.net/iau/MPCORB.html

Our simulations suggest, that the disruptions and consequent orbital evolution of created fragments of rubble-pile asteroids approaching Earth qualitatively differ from those taking place near Mars. This is most likely due to the different scale of tidal forces of Mars and Earth acting on NEOs approaching them and also due different magnitude of acting gravitational perturbing forces, effecting the evolution of families' members.

According to our tidal disruption simulations, rotating progenitors were more prone to the disruption, confirming the results of Richardson et al. (1998) and Walsh el al. (2006). Out of total 718 runs, 16.7% of objects underwent a disruption, which is in contrary to non-rotating objects, were only 2.4% of all progenitors suffered any kind of mass loss during close encounter with Earth. Non-rotating parents require very low encounter velocities and close approaches to Earth for disruption to occur, compared to rotating objects. It can be expected, that similar trend, where increase of spin period leads to increase of disruption probability can also be observed for disruptions near any other planet.

The type of disruption is one of the factors determining the likelihood of detection of a NEO family. A violent disruption, where a 'string-of-pearls' configuration of fragments with similar masses is created, is most likely to be detected. The likelihood, that Mars-approaching asteroid disrupts and creates a family with similar-sized fragments is only 11.1%. In case of Earth-approaching asteroids, the chance of creating a 'string-of-pearls' disruption is slightly higher, ~27.5%. Mild disruptions, where the largest fragment retains more than 90% of original mass are most likely both for disruptions near Earth and Mars. This is a great difference compared to the majority of known MBA families created by violent collisions, which shatter the parent object. Average NEO family is composed of two-three larger members, several hundreds of meters in diameter, and a swarm of smaller fragments, up to hundred meters in diameter. Thus it is very likely, that disruption events are able to produce meteor streams with large fraction of very bright fireballs when colliding with Earth.

We have calculated the ejection velocity distribution of members of all tidally disrupted families (from both Mars- and Earth-groups), from the post-disruption coordinates of the fragments. The $\boldsymbol{v_{ej}}$ value was calculated with respect to the largest object in the family. For most of the families from both groups $\boldsymbol{v_{ej}} \sim 0.4$ m.s^{-1}, which is two orders of magnitude less than an ejection velocity during a catastrophic collision in the main belt (e.g. Bottke et al., 2001). Tidal disruption is then a very gentle event comparing to the collisions in the main belt, in fact, the peak of escape velocity for our families is about a half of the escape velocity of a 1 km rubble-pile NEA. However, the reaccumulation of smaller clumps into a larger fragment, or into a whole asteroid is unlikely, because the fragments are not gravitationally bound anymore. Post-disruption separation between individual fragments is large and can be as much as several hundreds of kilometers.

In summary our simulations yielded 120 NEO families from the Earth-group with a rotating progenitor and 17 with non-rotating one, with number of fragments varying between 10 and 190. We've also obtained 9 NEO Mars-group families containing 13 to 90 members. The absolute magnitude of fragments varied in interval $14 < H < 22.5$.

3.2 The lifetime and evolution of NEO families

In order to assess the average lifetime of NEO families we extracted orbital elements of each member of each family from the integration output files in certain epochs from disruption in order to analyze the evolution of inspected parameters. Then we applied our cluster search algorithm on the synthetic NEO model and on every NEO family at the selected epoch. We have included only gravitational forces in our integrations, because the orbits of kilometer-sized NEOs are influenced by non-gravitational forces only on long timescales. For example, the expected drift rate for a 100 meter-sized diameter NEO is only ~2×10^{-4} AU in 10^5 years (Fu et al. 2005), considering $a = 1$ AU, $i = 45º$, typical density, albedo and surface conductivity.

Our results suggest, that the decoherence of all NEO families is extremely rapid, comparing to the families in the main belt. The range of lifetime is very wide - starting from several hundreds of years to more 10^6 yr. Due to the chaotic dynamical environment in the NEO region, families not only spread out into the space, but are also losing their members completely, when they enter a resonance and are transported on hyperbolic, or Sun-grazing orbits. Also collisions with terrestrial planets act as one of the major sinks for the members. Some families can remain tightly clustered (and thus detectable) for a very long time, whilst some can dissipate extremely fast, when post-disruption orbits of the members are changed in such a way, that their enter one of the resonances acting in the inner Solar system. Gladman et al. (2000) have shown, that the secular resonances ν_2 and ν_5 at high eccentricities placed between $1.3 < a < 1.9$ AU, in particular provide the routes to the Sun-grazing end states of NEOs. Typical NEO also suffers numerous close encounters during its lifetime, which are again able to significantly change the orbits.

Due to their rapid decoherence families can be distinguished from the background only for limited time. That time depends on the limits set on the compactness of family (determined by the cutoff value in cluster-search), and by the density and features of background population. Because statistical significance is impossible to prove for NEO triplets, we claim a family to be dissociated (the terminal point of a family `lifetime'), when the number of family members identified is less than 4.

In order to determine the detectability of the families, we have used the original Dc-Dp cutoff values from (Fu et al. 2005), and compared the average values of SCR, PF and average D_{SH} - $\boldsymbol{D_{av}}$ from all 120 families created near Earth at selected epochs to the clusters found with the same thresholds in the synthetic model. The general trend is D_{av} increasing with time, as the families get dispersed and the orbits of members are changing with respect to each other. At the same time the values of SCR and PF decrease, reflecting that the pairs within the cluster get looser and some members are leaving the core of the family. Compared to the synthetic model, families can be distinguished up to 10^5 years from creation, after that their values of SCR, PF and D_{av} resemle those of false clusters in the synthetic model.

It seems, that under certain conditions, a NEO family can 'settle' in a stable region, where the planetary perturbations are mild, and even if it would lost several loosely bound members, which cross the D_c boundary, it still retains a tightly bound core and can remain like that for several hundreds of thousands of years. In light of these results we believe, that given a higher density of NEA population today, using lower D_c and D_p thresholds would be appropriate to estimate the lifetime of NEO families. We have empirically chosen $D_c = 0.06$ and $D_p = 0.05$, because they are roughly the half of the values Fu et al. (2005) had used, and also $D_{av} = 0.06$ approximately borders the area detectability of NEO families during their evolution, before entering the region of false clusters in synthetic model.

Our simulations yield the average lifetime of a family created by tidal disruption during a close encounter with Earth 8.0±20.1x 10^4 yr, and the average lifetime of families created by tidal disruption during a close encounter with Mars 39.9±37.5 x 10^4 yr. The large RMS reflects the distribution of lifetimes for both groups, and takes into account for how long the family retains more than 3 members. It also includes the occasional fluctuation of all parameters, which make it undetectable for short periods of time. The lifetime is indeed dependent on the chosen values of D_c and D_p. In case of Earth, the distribution of lifetimes drops more rapidly, and as a result only 51.2\% families is detectable after 10,000 years. If reflects the fact, that only a handull of members of each family remains clustered enough to fulfill such a strict thresholds. This trend can also be observed in case of Mars, but the drop of lifetimes is only moderate.

Used thresholds		Average lifetime [10^3 yr]	
D_c	D_p	Earth	Mars
0.112	0.100	79.6	704.4
0.06	0.05	44.0	399.0

Table 1: Average lifetimes of NEO families created near Earth and Mars, depending on the D_c and D_p cutoffs. The tighter the cutoffs, the shorter is time during which a NEO family can be identified. Lifetimes in the table take in the account the oscillations in detectability of some cases.

However, we need to be careful about the conclusions driven from results for Mars, because we've only had 9 simulated families available, and this statistical sample is rather small to allow us to state an meaningful conclusion about nature of families created near Mars in comparison to ones created near Earth. Our simulations indeed suggest, that the dissipation if an average family from Mars-group is slower than of the one form the Earth-group, but more detailed analysis showed, that by 10^5 years after disruption, 7 out of 9 families crossed the NEO region boundary at $q < 1.3$ AU and actually joined the region known as 'Mars-crossers'. Objects in this region have an average lifetimes roughly 29 x 10^6 yr, thus a longer lifetime of families which dwell there is a natural consequence. Mars-crosser population is thus also a very promising place to look for grouping of genetically-related asteroids.

This result also means, that disruptions near Mars are most likely not an significant contributor to the NEO family population. But it is necessary to test this hypothesis by results from a larger sample of families, which would be the topic of our future work.

Also one has to keep in mind, that the estimate of lifetime in terms of „detectability“ mentioned above is only rough, it reflects the dispersion of members, but doesn't account for observational selection effects. Additional measures, such as statistical analysis must be taken in case for search for a NEO family in real population.

3.3 Number of NEO families in the population

In case of NEO families, we are facing two issues. First is the number of NEO families present in the population at any given time, which is the function of flux of the families into the population, and their lifetime. Second is the fraction of existing families, that can be actually detected, considering the density of background population, and the observational selection effects. In our work we focused on the former problem.

The number of NEO families present in the population - N_{fam} is determined by numerous factors, from which only a handful are currently known in sufficient detail:

1. number of NEAs in the steady-state population - $N_{NEA}(H)$
2. probability of close encounters (< 3 R_{pl}) with a certain planet - P_{CE}
3. probability of tidal disruption P_{TD}
4. probability of creating a „string of pearls" type of disruption- P_{TS}
5. NEO family lifetime - ***L***

All contributing factors, except for the first one have to be evaluated separately for each one of the terrestrial planets, because NEAs do have unique pre-encounter parameters with every planet. Values of ***L***, P_{TD} and P_{TS} are direct results from our simulations. P_{CE} could be calculated with available data. $N_{NEA}(H<20)=3020$, which is the number of such objects present in the mpcorb.dat database. This number is also close to the estimate of steady-state $N_{NEA}(H)$ from Bottke et al. 2002. The mean intrinsic collision probability P_{col} of NEAs with terrestrial planets and Moon had been calculated by Bottke et al. (1994). In our approach we consider every object which approaches a planet within 3 its radii as a close encounter. Thus in order to estimate the probability of such event and also lifetimes of actual planet crossers we multiply given average intrinsic collision probability by the square of 3 times the actual planetary radius.

Using the values of parameters as described above, in case of the NEO families created by disruption near Earth, the probability of close encounter within 3 Earth radii is $P_{CE} = 7.99 \times 10^{-8}\ yr^{-1}$. Such deep encounters with Earth then occur with a frequency 12.5×10^{-6} yr. Similarly for Mars $P_{CM}=2.7 \times 10^{-9}\ yr^{-1}$, and a close encounter with Mars should occur every ~ 370×10^{-6} yr. However, current probability is most likely higher, simply due to discovery of many more objects crossing Mars' orbit since 1994.

The number of NEO families present in the population at any given time can be in general defined as N = F . L, where ***L*** is the lifetime of a NEO family, which can be obtained from numerical integration of our simulated family members, and ***F*** is the flux of NEO families into the NEO region, where

$$F = N_{NEA}(H).\langle P_{CE}\rangle.\langle P_{TD}\rangle.\langle P_{TS}\rangle \tag{3.1}$$

When we substitute the variables by available data and our simulation results, and evaluate the equation (3.1) we get $N_{fam,\ E}$ = 0.89. Which means there should be roughly one NEO family form Earth-group present in the population at any given time. Again, in the same way as as for Earth, we can estimate the number of families created by tidal disruptions of a NEO during a close encounter with Mars, and after evaluation of equation (3.1) we get $N_{fam,\ M}$ = 0.06, which is an order of magnitude less than we calculated for Earth.

However, the estimate on number of families created near Mars needs to evaluate close encounters of two types of progenitors - NEOs, and Intermediate source Mars-crossers (IMC). IMCs can be an important contributor to the number of NEO families, because objects from the Mars-crosser population have very low encounter velocities with Mars. According to simulations, we can estimate, that 4.23% IMCs suffers close encounter with Mars (B. Bottke, personal communication). That means, that only 1 object approaches Mars within 3 Mars radii every 75,000 years. Thus a rough estimate of close encounter probability of a IMC is 1.46 x 10^{-9} yr^{-1}, which gives us $N_{fam,\ MC}$ = 0.11. Together with Mars-group families originating from a NEO parent, the number of families present in the NEO population produced by Mars' tidal forces is roughly 0.17.

With Earth as the major contributor there should be roughly 1 NEO family present in the population at any given time. The fact, that there should be ~1 observable NEO family at any time, and we are currently seeing none, as described section 3.4 suggest, it is a reasonable estimate, given the fact that the observational bias has not been accounted for in our analysis.

3.4 Searching for NEO families in the real population

In the last part of our work we searched for the NEO families in the real population using the results and knowledge from our simulations. We identified three clusters of four or more members in the the mpcorb.dat orbital database. The three clusters are labelled C1, C2 and C3, and have 4, 6 and 5 members respectively. The absolute magnitudes of the cluster members spans $18.5<H<29.5$, corresponding to diameters ranging from several meters up to several hundreds of meters depending on the choice of albedo. We searched for clusters containing 4 and more members over the range of D_c-D_p space with $0.040 \leq D_c \leq 0.060$ where $D_p<D_c$, using fixed SCR_{min} = 0.75 and PF_{min}= 0.5. The clusters can be identified over a

limited range D_c-D_p with the most statistically significant point typically having the smallest D_c-D_p.

In order to confirm their origin we performed an statistical analysis, for which we had developed NEO models that maintained both the micro and macro distribution of 5 orbital elements (ignoring the mean anomaly) and also eliminated any possible real clusters. In every model we „fuzzed“ the orbital elements of each object around its position in 5-dimensional orbital element space in a manner that maintained the local orbital element phase density and thereby preserves both the intrinsic NEO orbital element distribution and the observational selection effects.

C1 cluster is statistically significant at ~ 2σ. The C2 and C3 clusters are likely even less significant based on the large errors of their orbital elements, which can eventually place them far away from each other in the orbital element space. It is important to remember that our calculated statistical significance of the NEO clusters hinges on the reliability of our fuzzy real NEO models. It is surprisingly easy to create NEO clusters with 4 and more members. Given that all 4 C1 members are relatively large NEOs with $H < 20$ were-did the entire search for clusters using only those NEOs with $H < 20$ and re-calculated their statistical significance. As expected, statistical significance of the C1 cluster increases to about 3σ because of the reduction in the total number of NEOs to ~ 3100. While we have taken every precaution in developing our NEO models we understand that they have their limitations. In spite of it, in the remainder of this work we consider only the C1 cluster as a candidate NEO family.

The most statistically significant cluster, C1, contains four objects with well-determined orbits with the largest member being asteroid 2000 HW23. We performed several additional tests of the C1 cluster's family veracity including checking the members' taxonomic identification, their bias corrected size-frequency distribution, the possibility that they originated in a family-producing tidal disruption at Mars about 71,000 years in the past, and whether it is also identifiable as a cluster in proper element space. None of these tests exclude the possibility that C1 is a genetically related family but at the same time none of the tests provide sufficient evidence to elevate the cluster to family status.

The search for families amongst the NEO population is clearly not as straightforward as the same search amongst the main belt population. Special care must be taken when assessing the statistical significance of a purported NEO family especially with regard to accounting for observational selection effects in the NEO population. At the very least, mere similarity of the orbital elements as evidenced is insufficient for deciding upon any genetic relationship between NEOs and by extrapolation, between NEOs and meteors.

References

Bottke, W. F., J., Nolan, M. C., Greenberg, R. & Kolvoord, R. A. (1994), Collisional Lifetimes and Impact Statistics of Near-earth Asteroids, in T. Gehrels, M. S. Matthews & A. Schumann, eds, '*Hazards due to comets and asteroids*', University of Arizona Press, pp. 336–357.

Bottke, W. F., Vokrouhlický, D., Brož, M., Nesvorný, D. & Morbidelli, A. (2001), 'Dynamical spreading of asteroid families by the Yarkovsky e□ect.', *Science* **294**, 1693-1696.

Bottke, W. F., Morbidelli, A., Jedicke, R., Petit, J. M., Levison, H. F., Michel, P. & Metcalfe, T. S. (2002), 'Debiased Orbital and Absolute Magnitude Distribution of the Near-Earth Objects', *Icarus* **156(2)**, 399–433.

Cellino, A., Bus, S. J., Doressoundiram, A. & Lazzaro, D. (2002), Spectroscopic properties of asteroid families, in W. Bottke, A. Cellino, P. Paolicchi & R. P. Binzel, eds, '*Asteroids III*', University of Arizona Press, pp. 633–643.

Chambers, J. E. (1999), 'A hybrid symplectic integrator that permits close encounters between massive bodies', *Monthly Notices of the Royal Astronomical Society* **304**, 793–799.

Drummond, J. D. (2000), 'The D-discriminant and Near-Earth Asteroid Streams', *Icarus* **146(2),** 453–475.

Fu, H., Jedicke, R., Durda, D. D., Fevig, R. & Binzel, R. P. (2005), 'Identifying near-Earth object families', *Icarus* **178(2),** 434–449.

Gladman, B. J., Migliorini, F., Morbidelli, A., Zappalá, V., Michel, P., Cellino, A., Froeschlé, C., Levison, H. F., Bailey, M. & Duncan, M. (1997), 'Dynamical lifetimes of objects injected into asteroid belt resonances', *Science* **277**, 197–201.

Gladman, B. J., Michel, P., Froeschlé, C. (2000), 'The Near-Earth Object Population', *Icarus* **277**, 176–189.

Gronchi, G. F. & Milani, A. (2001), 'Proper Elements for Earth-Crossing Asteroids', *Icarus* **152**, 58–69.

Hirayama, H. (1918), 'Groups of asteroids probably of common origin', *Astronomical Journal* **31(743),** 185–188.

Ivezić, v., Lupton, R. H., Jurić, M., Tabachnik, S., Quinn, T., Gunn, J. E., Knapp, G. R., Rockosi, C. M. & Brinkmann, J. (2002a), 'Color Confirmation of Asteroid Families', *The Astronomical Journal* **124**, 2943–2948.

Knežević, Z., Lemâıtre, A. & Milani, A. (2002), The Determination of Asteroid Proper Elements, in W. Bottke, A. Cellino, P. Paolicchi & R. P. Binzel, eds, '*Asteroids III*', University of Arizona Press, pp. 603–612.

Morbidelli, A., Bottke, J. W. F., Froeschlé, C. & Michel, P. (2002), Origin and Evolution of near-Earth Objects, in W. Bottke, A., Cellino, P., Paolicchi & R. P. Binzel, eds, '*Asteroids III*', University of Arizona Press, pp. 409–422.

Nesvorný, D., Jedicke, R., Whiteley, R. J. & Izvezić, Z. (2005), 'Evidence for asteroid space weathering from the Sloan Digital Sky Survey ', *Icarus* **173(1),** 132–152.

Ohtsuka, K., Arakida, H., Ito, T., Yoshikawa, M. & Asher, D. J. (2008), Apollo Asteroid 1999 YC: Another Large Member of the PGC?, in '*71st Annual Meeting of the Meteoritical Society*', Annual Meeting of the Meteoritical Society **#71**, p. 5055.

Richardson, D. C., Bottke, W. F. & Love, S. G. (1998), ‘Tidal Distortion and Disruption of Earth-Crossing Asteroids’, *Icarus* **134**, 47–76.
Richardson, D. C., Elankumaran, P. & Sanderson, R. E. (2005), ‘Numerical experiments with rubble piles: equilibrium shapes and spins’, *Icarus* **17**3, 349–361.
Vereš, P., Klačka, J., Kómar, L. & Tóth, J. a. (2008), ‘Motion of a Meteoroid Released from an Asteroid’, *Earth, Moon, and Planets* **102(1),** 47–51.
Walsh, K. J. & Richardson, D. C. (2006), ‘Binary near-Earth asteroid formation: Rubble pile model of tidal disruptions’, *Icarus* **180(1),** 201–216.
Walsh, K. J. & Richardson, D. C. (2008), ‘A steady-state model of NEA binaries formed by tidal disruption of gravitational aggregates’, *Icarus* **193(2),** 553–566.
Whipple, F. (1983), 1983 TB and the Geminid Meteors, in B. Marsden, ed., ‘*IAU Circular* **#3881, 1’**, IAU.

Abstract

We present the results of a quantitative study of genetically related asteroids amongst the near-Earth object (NEO) population - NEO families. We focus on the subset formed by tidal disruption during a close encounter with Earth and Mars, where the events are most likely to happen. This study combines disruption simulations of the parent NEOs in form of a gravitational aggregate: a fragile `rubble pile', with the subsequent numerical integration of fragments. Out of several factors that determine the disruption likelihood, we confirmed, that the break-up of parent object is strongly ruled by spin.

We show that the dissipation of family members is extremely rapid compared to main belt asteroid families. We used the method of Fu et al. (2005) to identify the simulated NEO families as a function of time. Our results suggest, that families created during a close encounter with Mars have an average lifetime 399.0±375 x 10^3 yr, where 22.2% of families are detectable for up ~10^6 yr after disruption. The average lifetime of families created by Earth's tidal forces is 79.6±201 x 10^3, which is almost five-times shorter. Both groups of families posses similar collisional risk to terrestrial planets, roughly 4%.

We used the results from NEO families simulations in search for genetically related asteroids amongst the real NEO population. We supplemented our cluster-search method with a detailed analysis of the statistical significance of the detected clusters. The statistical significance was assessed by comparison to identical searches performed on 1,000 family-free NEO orbit distribution models that we developed for this purpose. Three clusters were identified that contain four or more NEOs. The most statistically significant cluster at the ~2σ level contains 4 objects with H<20 with long observational arcs and concomitant good orbital elements. We examined the cluster's taxonomy, size-frequency distribution, consistency with a family-forming event during tidal disruption in a close approach to Mars, and whether it also detectable in a proper element cluster search. None of these tests exclude the possibility that the cluster is a family but neither do they confirm the hypothesis. We conclude that we have not identified any NEO families.

Key Words: NEO, ASTEROID FAMILIES, DYNAMICS, ORBITS

List of publications

Benedikovič, Z. - Gajdoš, Štefan 80% - Schunová, Eva : Analýza zákrytových pozorovaní na AGO
Lit. 5 zázn., 3 obr., 1 tab.
In: Meteorické správy Slovenskej astronomickej spoločnosti pri SAV, Č. 28. - Banská Bystrica : Slovenská astronomická spoločnosť, 2007. - S. 91-98

Schunová, Eva 50 % - Buček, Marek 50 %: Komplexy malých telies slnečnej sústavy
Lit. 26 zázn.
In: Meteorické správy Slovenskej astronomickej spoločnosti pri SAV, Č. 30. - Banská Bystrica : Slovenská astronomická spoločnosť, 2009. - S. 52-62

Schunová, Eva 80% - Walsh, K. J. 10% - Granvik, Mikael 5% - Jedicke, Robert 5%: Rodiny medzi blízkozemskými asteroidmi
Lit. 11 zázn.
In: Meteorické správy Slovenskej astronomickej spoločnosti pri SAV, Č. 32. - Banská Bystrica : Slovenská astronomická spoločnosť pri SAV, 2011. - S. 63-70

Porubčan, Vladimír 25% - Svoreň, Ján 25% - Neslušan, Luboš 25% - Schunová, Eva 25%: The updated IAU MDC catalogue of photographic meteor orbits
Lit. 12 zázn.
In: Meteorids Conference. - Huntsville : NASA, 2011. - S. 338-341. - (NASA/CP ; Vol. 2011-216469)
[Meteoroids 2011 : The Smallest Solar System Bodies. Breckenridge, 22.-28.5.2010]

Hsieh, Henry H. - Yang, Bin - Haghighipour, Nader - Novaković, Bojan - Jedicke, Robert - Wainscoat, Richard J. - Denneau, Larry - Abe, Shinsuke - Chen, Wen-Ping - Fitzsimmons, Alan - Granvik, Mikael - Grav, Tommy - Ip, Wing - Kaluna, Heather M. - Kinoshita, Daisuke - Kleyna, Jan - Knight, Matthew M. - Lacerda, Pedro - Lisse, Carey M. - Maclennan, Eric - Meech, Karen J. - Micheli, Marco - Milani, Andrea - Pittichová, Jana - Schunova, Eva - Tholen, David J. - Wasserman, Lawrence H. - Burgett, William S. - Chambers, K. C. - Heasley, Jim N. - Kaiser, Nick - Magnier, Eugene A. - Morgan, Jeffrey S. - Price, Paul A. - Jørgensen, Uffe G. - Dominik, Martin - Hinse, Tobias - Sahu, Kailash - Snodgrass, Colin: Observational and Dynamical Characterization of Main-belt Comet P/2010 R2 (La Sagra)
In: The Astronomical Journal, Volume 143, Issue 5, article id. 104, 2012.
DOI: 10.1088/0004-6256/143/5/104

Schunová, E. 70% - Granvik, M. 10% - Jedicke, R. 5% - Groncchi, G. 5% - Wainscoat, R. J. 5% - Abe, S. 5%: Searching for the first Near-Earth Object family, SUBMITTED TO ICARUS, 2012.