The orbital clusters among the near Earth asteroids

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ABSTRACT

Fifteen orbital clusters (associations) were identified among \( \sim 20000 \) near Earth asteroids (NEAs). All associations were found with a high statistical reliability, we used a single linkage cluster analysis algorithm and three orbital similarity functions. Identified groups are a small fraction (4.74\%) of the whole sample. However they could be hazardous to the Earth and its inhabitants. Every year similarly as it happens with meteoroid streams, the Earth comes very close to the orbits of each association. In two cases (2008TC3 and 2017FU102) the distance between the asteroid orbit and the Earth’s orbit was smaller than the radius of our planet. Among members of the identified associations we found 331 objects larger than the Chelyabinsk asteroid and all these objects approach the Earth’s orbit at a distance smaller than 0.05 [au].

Two of the identified groups (4179) Toutatis and (251430) Itokawa, proved to be in favor of a catastrophic origin of Toutatis and Itokawa asteroids.

In this study we were not interested in the origin of the identified groups. However, regardless of their origin, in view of the serious thread to the Earth, tracing the NEA associations is very important issue. To facilitate their monitoring of we have calculated coordinates of the theoretical radiants and calendar date of their potential activity.

Key words: methods: data analysis–minor planets – NEAs

1 INTRODUCTION

The existence of the main belt asteroid (MBA) families is accepted beyond the doubts. The existence of families among the near Earth asteroids (NEAs) is an open issue, similarly to the problem of the genetic association of comet groups and pairs. In Kresak (1982) the author wrote “... to illustrate the diversity of opinions on this issue, it may be quoted from Opik (1971), that there are at least 60 groups of two or seven known comets which are due to real genetic associations.” “... and from Whipple (1977), that except for a few pairs these groups exhibit similarity in their orbital elements that is no greater than might be expected by chance.”

The search for grouping amongst the NEAs, does not have a very long history. Almost twenty years have passed, since an extensive search for grouping amongst NEAs was performed by Drummond (2000). Among 708 NEAs he found 14 associations of 4-25 members. Drummond estimated that more than half of them might be attributed to chance alignments. This study was followed by that of Fu et al. (2005), these authors made critical study of Drummond’s results and confirmed his skepticism. Fu et al. concluded “… Drummond’s families are nothing more than random fluctuations in the distributions of NEA osculating orbital elements.” Schunová et al. (2012) searching for families amongst \( \sim 7500 \) near Earth objects (NEOs), affirmed that they have not identified any NEO family. The variant results were found by Jopek (2011a, 2015) and recently by De la Fuente Marcos & De la Fuente Marcos (2016). Jopek amongst \( \sim 9000 \) found more than ten groups of more than ten members. De la Fuente Marcos & De la Fuente Marcos (2016) examining the orbits of \( \sim 13500 \) NEOs reached the conclusion that they confirmed the presence of statistically significant dynamical groupings among the NEO population.

The above mentioned studies gave different results, which is understandable because searching for families (members originating from the same parent body) or searching for associations (members displaying the orbital similarity only) are two different tasks. However, regardless of their origin, when abundant families or just associations exist, we deal with the increase in the threat they might pose to the Earth. And this implies that the search for grouping amongst the NEA’s is an important issue.

In this study, applying the cluster analysis method, developed and validated for the meteoroid stream searching (Jopek 2011b), we made an extensive and statistically strict search for associations amongst \( \sim 20000 \) NEA’s orbits.
We used heliocentric ecliptical osculating elements by Kholshevnikov et al. (2019) and Jopek (2016). Also the NEAs sample is dominated by low inclination (Popova et al. 2013). NEAs. Low inclined orbits predominate, the median inclination $i = 5^\circ$. Also small MOIDs predominate, the median MOID $D_{\text{MOID}} = 0.0550 \text{[au]}$. This is not superfluous to note that Chelyabinsk object had the diameter $\sim 20 \text{[m]}$ (Popova et al. 2013).

2.2 Searching method

Our searching method comprise of three components:

- **cluster analysis algorithm** — we used a single linkage method (a variant of general hierarchical cluster analysis method) proposed for the meteoroid stream identification by Southworth & Hawkins (1963).

- **orbital similarity function** — we used the hybrid D-function $D_H$ proposed by Jopek (1993b) and two $\rho$-functions ($\rho_1, \rho_2$), applied in Kholshevnikov et al. (2016). Mathematical formulas and more details about different D- and $\rho$- functions one may find in Williams et al. (2019).

- **orbital similarity thresholds** were determined using a statistical approach; the thresholds were found separately for each group of $2, 3, ..., M=50$ members, and for each $D_H, \rho_1, \rho_2$ functions. All thresholds corresponded to low probability (less than 1%) of chance grouping.

The orbital similarity thresholds were determined by numerical experiment (similar to the one described by Jopek & Froeschlé (1997); Jopek et al. (2003)), namely:

- we searched for grouping in the synthetic orbital samples starting from $D_0$ for which no single group of $2, 3, 4, ..., M=50$ members were found,

- next, search for groups was repeated with an increased value of $D_0$ until the first group of $2, 3, 4, ..., 50$ members, respectively, were found and the obtained $D_{\text{MOID}}$ corresponding to the previous step were stored,

- when the last $D_{\text{MOID}}$ value was found the new synthetic orbital sample was searched. For each distance function 100 synthetic orbital samples were searched.

The final individual thresholds $D_M, M=2, 3, 4, ..., 50$ were calculated as the arithmetic means of one hundred of $D_{\text{MOID}}$ values.

The synthetic NEA orbits were generated using inversion of the cumulative probability distributions of the observed sample, by the method $C$ described in Jopek & Bronikowska (2017). Only these synthetic orbital samples were used which had passed the consistency test with the observed sample. The chi-square test was applied, see Press et al. (2002). Before the final thresholds $D_M$

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1 The database is publicly available at the URL https://newton.spacedys.com/neodys/index.php?pc=5

2 We applied definitions given at https://cneos.jpl.nasa.gov/about/

3 We used the software and data file from https://ssd.jpl.nasa.gov/
were determined, the possible groups in the observed NEA sample were excluded. They were identified by the same cluster analysis as described above. After elimination of clusters, the orbital distributions of the observed reduced sample were used to determine the final thresholds $D_M$.

To estimate the sensitivity of $D_M$ values to the assumed parameters of our synthetic orbits generation method, we made several additional simulations. We checked the influence of the size of the histogram bins and the choice of the seed of the uniform random number generator. Fig. 3 shows that the thresholds (an example for the $\rho_1$ function is given) are not sensitive to the choice of the histogram bin size. A similar dependence was found changing the seeds of the random number generator. The same behavior we found for the remaining functions.

Finally we determined the medians of the $D_M$ values obtained from different bins and seeds. Their arithmetic means are given in Table 1, and these values were applied in this study.

3 GENERAL RESULTS

Results of all nine searches are summarized in Table 2. 18–22 associations were found which include 3.6–5.1% orbits of the whole NEAs sample. The obtained percentage values are considerably lower than in the meteor streams searching, e.g., in Southworth & Hawkins (1963) of the 359 photographic orbits about 36% belonged to streams, in Jopek (1986) of the 1608 photographic orbits about 58% belonged to streams, in Jopek (1993a) of the 531 TV meteor orbits about 30% belonged to stream component, in Jopek et al. (1999a) of the 3675 radio orbits about 28% belonged to stream, in Jopek et al. (2003) of the 256 bolides about 29% belong to streams. Of ~19000 radio-meteoroids only about 16% belonged to streams (Sekanina 1976).

For each individual distance function, the results are quite consistent, while the results obtained with $D_t \pm \epsilon$ thresholds are similar. However, they differ when different functions are compared. Most associations, 22, were found using the $\rho_1$ function, their sizes were rather small, the most numerous group consisted of 292 members. Also, using the $\rho_1$ function the associations made the highest 5.1% of the total sample. Concerning the number of identified groups the searches with $D_H$, $\rho_1$, $\rho_2$ gave reasonably similar results. The most stable results were obtained with $\rho_1$ function, the largest groups (above 400 members) were identified with $\rho_2$ metrics.

Such diverse results hamper the interpretation of the cluster analysis, but in the case of small bodies of the Solar System such differences are not surprising. Similar differences were observed in our earlier studies described in Jopek (2011a,b, 2015). They are caused by different properties of the orbital distance functions. Different $D$- and $\rho$- functions are not equivalent to each other (see Jopek 1993b; Kholshevnikov et al. 2016), they are expressed by different mathematical formula and depend on different number of variables: five in the case of $D_H$ and $\rho_1$, six in the case of $\rho_2$.
function. These sets of variables refer to different spaces, therefore it is nothing special that using distinct orbital distance functions we get different results of the cluster analysis. Hence, the problem is to decide — how we should extract from this complicated picture the most robust associations?

In what follows we discuss the results obtained with $D_H$, $\rho_1$ and $\rho_2$ function. No single association of 3 or more members was found by all functions identically, some groups were found using one distance function only, but for many groups a partial overlap occurred. The most consistent result, found by all functions are two very compact pairs: 2015FO33, 2015YZ and 2017SN16, 2018RY7. On the other hand, one of a very complicated result is the huge association found with the use of $\rho_2$ function with the threshold $D_H=0.0566$, it is designated by the code $\rho_2/296$ and consists of 495 members. (In this study we designate the association by the D-function and the running number (in our data sample) of the first NEA which belongs to this group.) The $\rho_2/296$ association was partly split into 2 sub-groups found by $D_H$ function and also into 2 sub-groups by $\rho_1$ function. Additionally, the $\rho_2/296$ association contained quite a few NEAs which were not included in the sub-groups in question. The $\rho_2/296$ proved to be our the most complex finding, but also for the other large groups we observed similar splittings.

In the next section, before more details about our finding are described, we present briefly the results obtained in similar studies by other researchers.

3.1 The results obtained before this study

We refer to these studies whose authors performed extended search for groups among the NEAs orbits only.

In Drummond (2000) the author searched among 708 orbits. Essentially, he applied different searching method, only when searching for pairs and strings he used a single linkage approach. Also, he used the $D_{SH}$ function proposed by Southworth & Hawkins (1963) and a single value of the orbital similarity threshold $D_{SH}=0.115$. Drummond found 14 associations of 4-25 members, 8 strings (i.e. groups of three members) and 7 pairs. His largest associations A1 included 25 members. All groups contained 22% orbits of the whole NEAs sample, whereas in our study this percentage equals 3.6-5.1% only. In our study we found many members of Drummond groups, however our findings were different, e.g. in our study Drummond’s A1 association split up into our DH/178 (5 members) and $\rho_1/659$ (1 member).

As was mentioned in section 1, Schunová et al. (2012) searched among 7500 NEAs for families only. They applied different cluster analysis and $D_{SH}$ function. Three clusters were found C1, C2, C3 of 4-6-5 members only and no cluster passed the strict significance family-test. In the present search, none of four objects of C1 group was identified as an association member; five of six members of C2 were in DH/3058 and $\rho_1/3058$. All five members of C3 were in our $D_H/955$. In our study, however, we do not claim that our groups which incorporate C2, C3 are the NEA families.

In our earlier search described in Jopek (2011a, 2015, 2019) we used similar approach as in this study, however, only very limited and general results have been presented. At the XXVIII IAU GA in Beijing, (Jopek 2015), we presented results of the search among 9004 NEAs. We accepted 10 associations which contained ~8% orbits of the whole sample. These findings are referred to in the following section.

Quite recently De la Fuente Marcos & De la Fuente Marcos (2016) searched for groupings among ~13400 NEAs orbits. They applied different cluster analysis algorithm as well as two different D-functions, namely the reduced $D_F$ function proposed by Valsecchi et al. (1999) and a simplified form of the $D_{SH}$ function proposed by Lindblad (1994). In their paper five groups are reported consisting of 43-180 members. Because the authors did not give a full list of members of the identified groups (only a few members were specified) it is difficult for us to refer to this study. We were only able to find that the mentioned 4 NEAs from their 5011 Ptah group do not belong to any group found in our search; from 3 NEAs mentioned as the 85585 Mjolnir group only one was found in our $\rho_2/3041$, $\rho_2/3041$ associations and from 2 members of the 101955 Bennu group mentioned by De la Fuente Marcos & De la Fuente Marcos (2016) only one we found in our $\rho_2/296$ association.

4 RESULTS AND DISCUSSION

In this section we describe details of 15 associations identified in this study. The association were named after the first asteroid in the NeoDys catalogue which belonged to the identified group. Also our working code was assigned which represents the distance function used, and the running number of the first orbit in our NEA catalogue assigned to the group. For each group we give the list of names of the members. The names of the NEAs which satisfy the condition corresponding to the Chelyabinsk object — the absolute magnitude $H \leq 26$ and the MOID$\leq 0.05$ [au] are given in bold characters. We call such an object as the Chelyabinsk class object that potentially threatens the Earth inhabitants at least to the same extent as in the case of the Chelyabinsk meteorite. The orbits belonging to the same association are graphically illustrated. The plotting projections were chosen differently, the orbital arcs running below the ecliptic are plotted in blue. All physical parameters like the absolute magnitude $H$ and diameters $d$ were taken from http://neo.ssa.esa.int/ or http://neo.ssa.esa.int/neo-home.
Figure 4. Anza (2061) association. 89 orbits resemble a meteoroid stream approaching the Earth orbit at distances 0.0006-0.1063 [au]. Activity of the potential bolides related with this group starts in August and ends in November. The orbital arcs running below the ecliptic are plotted in blue. The projection of the Earth orbit lies inside Anza association. In the bottom right corner there is an arc of the Jupiter orbit.

4.1 (2061) Anza association

Anza association (our internal code $D_H/23$) was named by the name of Anza NEA of absolute magnitude $H=16.38^m$ and diameter $d=1700$ [m]. The group consists of 89 members (see Tab. 3), it was identified using $D_H$ function with the orbital similarity threshold $D_t = 0.047386$. Anza was found in our earlier search among ∼9000 NEAs (see Jopek 2015), at that time only 34 orbits of the group were identified.

The orbit of 2008VB4 ($H=28.32^m$), the member of this association, approaches the Earth’s orbit very closely, its MOID equals 0.000562 [au], or 0.219 [LD] i.e. the mean Earth-Moon distance. Parameters of the theoretical radiant of this NEA are: the equatorial coordinates $\alpha_G=251^\circ$, $\delta_G=-22^\circ$ and the geocentric velocity $V_G=11.9$ [km/s]. Potential meteor-bolide activity related with this radiant falls on November 4th. The remaining orbits of the Anza group do not approach the Earth’s orbit so closely, however many of them reach the MOIDs smaller than 0.05 [au]; the maximum MOID is 0.1063 [au], the average one is 0.0326 [au]. From this group 38 members come under the Chelyabinsk class, 5 objects meet the PHAs criteria. In outer space, the orbits of Anza group form a structure which resemble a typical meteoroid stream, as illustrated in Fig. 4. The names of the members of this association are listed in Tab. 3.

Anza asteroid was included by Drummond (1991) as a member of association II in his Table II. However, the other members of this group ((3351) Verenie, (496817) 1989VB, (3908) Nyx and (2202) Pele) were not identified as the members of our Anza association. Hence, our finding does not confirm the Drummond’s result.

4.2 (12923) Zephyr association

Zephyr group (DH/178, $H=15.7^m$, $d = 2060$ [m]) was identified by $D_H$ function and $D_t = 0.047304$. It consists of 51 orbits observed up to AD 2012 and 81 observed since 2012. In our previous search (Jopek 2015) this association was named as the NEA Masaakikoyama (13553). Total 132 orbits (see Tab. 4), form a meteoroid stream like structure (see Fig. 5), however, not as coherent one as the Anza association. The smallest MOID for this group is 0.000157 [au] or 0.0611 [LD]. We found it for asteroid 2018SM ($H = 29.4^m$). Parameters of the theoretical radiant of this NEA are: $\alpha_G = 217^\circ$, $\delta_G = 20^\circ$, $V_G = 10.2$ [km/s]. Potential meteor-bolide activity of this radiant falls on September 17th. The maximum MOID in Zephyr group equals 0.02768 [au], the average one is 0.1417 [au]. From this group 14 members are of the Chelyabinsk’s class, 6 objects meet the PHA criteria.

Table 3. Codes of the members of Anza (2061) association. 89 members were identified by $D_H$ function, a single linkage cluster analysis algorithm and the orbital similarity threshold $D_t = 0.047386$. 38 objects printed in bold are of the Chelyabinsk’s class.

![Table 3](image)

Figure 5. Two plots of the orbits of Zephyr (12923) association. At the top, 51 orbits observed before AD 2012, at the bottom, 81 orbits observed during the period 2012–2019. The drawings are similar to each other.
Table 4. Zephyr (12923) association. 132 members were identified by $D_{H}$ function, a single linkage cluster analysis algorithm and the orbital similarity threshold $D_f = 0.047304$. 14 objects printed in bold are of the Chelyabinsk’s class.

| Object  | $\rho$ [LD] | $a$ [au] | $e$ | $i$ [°] | $\omega$ [°] | $\Omega$ [°] | $T_{\text{per}}$ [yr] | $T_{\text{op}}$ [yr] | $T_{\text{c}}$ [yr] |
|--------|-------------|----------|-----|--------|------------|------------|----------------|----------------|----------------|
| 12923  | 0.000102    | 4.3 (4179) T outatis association. |

4.3 (4179) T outatis association

Association T outatis (internal code $\rho_1$63) is named after the most massive object in the group, $H = 15.2^m$, size 4750x1950 [m]. It was identified using $\rho_1$ and $D_{H}$ function, 173 (see Tab. 5) and 211 members, respectively. The group resemble dispersed, but still coherent meteoroid stream. The inclination of the orbits is small (up to 6.7°); many orbits approach closely the Earth orbit at the ascending and descending nodes. T outatis orbital inclination equals 0.45°, its orbit occupies central position in the group, see Fig. 6. The minimum, maximum and mean MOID for this group are: 0.000102 [au] or 0.039695 [LD]; 0.182691 [Au], 0.036038 [au], respectively. The minimum is for 2017FU102 NEA and the radiant parameters are $\alpha_G = 323^\circ$, $\delta_G = -18^\circ$, geocentric velocity $V_G = 9.5$ [km/s]. Potential meteor-bolide activity of this radiant falls on September 22nd. 71 members of the T outatis association are of the Chelyabinsk’s class.

The hypothesis that T outatis is a member of the NEA group, in the context of Taurids Complex, was raised by Asher et al. (1993); Steel et al. (1993); Steel (1994). In Steel (1994) choosing Southworth and Hawkins D-function (Southworth & Hawkins 1963) and $D_f = 0.25$, T outatis was listed among 22 other NEAs as having orbits similar to those of the Taurid meteoroid complex. In our search however, none of the 22 orbits was found among our T outatis group.

Discussing if T outatis is a member of the NEA family, Steel wrote: "Asteroid (4179) T outatis is of some topical interest since it had a near-miss of the Earth in 1992 December, radar images showing it to have a bifurcated structure. This might be understood in terms of a hierarchical disintegration, several subunits having already separated, leaving two still in contact. This interpretation would be bolstered by the identification of other NEAs on similar orbits as T outatis, indicating that a family has been produced by the break-up of a larger object...". On December 2012, the close observation of T outatis accomplished by Chang’e-2 spacecraft, (Huang et al. 2013) confirms Steel’s speculations. The bifurcated configuration implies a contact binary for T outatis. The other

4.4 (25143) Itokawa association

This group (DH/227) was identified by $D_{H}$, $\rho_1$ as well as by $\rho_2$ function. The numbers of identified NEAs were 94, 128, 106, respectively. One of the most massive object in the group is the asteroid Itokawa (25143), $H = 18.95^m$, size 520x270x230 [m], 94 members of the group were identified with $D_{H}$ and $D_f = 0.047529$.

The group resembles quite a coherent meteoroid stream. The inclinations of the orbits are small (up to 6.5°), many orbits approach closely the Earth orbit at both nodes. Itokawa orbital inclination equals 1.62°, the orbit approaches the Earth orbit within 0.013 and 0.023 [au] on 28th June and 4th April, respectively. It occupies internal position in the group, see Fig. 7. The minimum, maximum and mean MOIDs of this group are: 0.000037 [au], 0.085742 [au], 0.022713 [au], respectively. The smallest MOID equals 0.014399 [LD] was found for 2017FU102, $H = 28.67^m$, $d_e = 6$ [m]. Such MOID is smaller than the Earth radius, and fortunately, at the date when our planet was close to this point the asteroid was very far away on its orbit. This small Earth MOID we calculate to have a near-miss of the Earth in 1992 December, as was written by Southworth and Hawkins D-function (Southworth & Hawkins 1963) and $D_f = 0.25$, T outatis was listed among 22 other NEAs as having orbits similar to those of the Taurid meteoroid complex. In our search however, none of the 22 orbits was found among our T outatis group.
of the Chelyabinsk’s class.

Table 6. Itokawa (25143) association. 94 members identified by $D_H$ function, a single linkage cluster analysis algorithm and the orbital similarity threshold $D_s = 0.047529$. 40 members of Itokawa association, including Itokawa asteroid, are of the Chelyabinsk’s class.

25143 89136 141018 2001DW10 2004DK1 2004HD
2004W10 2006IN10 2006E1Y 2006E3N30 2006TJ4 2006KL103
2007EG88 2007EB13 2007T18 2008C71 2008BZ2 2008LE
2009DN4 2009FH 2009FK 2009BB21 2010CE5 2010BF
2010JS9 2011E3C 2011P79 2011GR59 2012BD2 2012BF32
2012E38 2012TV221 2012PH2 2012PJ1 2012KD12
2013ED8 2013EN20 2013E9 2013J612 2013FB1 2013JF1
2013MT28 2014DG80 2014DB12 2014FZ2 2014GI48 2014HA199
2014EX48 2014H56 2014HT179 2014HJ179 2014QV4 2014QW4
2015CW13 2015D0K20 2015FC345 2015K5120 2015BB117 2015KD57
2015KK120 2015M54 2016C735 2016E88E 2016EDQ1 2016FWN13
2016GH10 2016GHO 2016FH 2016TM12 2016TP46
2016JN89 2016TV22 2017PS149 2017TJ2 2017LE328 2017W4
2018DN1 2018DV3 2018ES54 2018ADH 2018PP4
2018PP23 2019CL2 2019ES 2019ES2 2019F9E1 2019GC
2019GCP 2019GC51 2019GI3 2019HI 2019PH1

2455400.5 [TDB]. The orbit of 2017FU102 is not well known, the data-arc span is 11 days parameters.

Theoretical radiant parameters related to the asteroid 2017FU102 are $\alpha_G = 178^\circ$, $\delta_G = 16^\circ$ and $V_G = 7.29$ [km/s] the date of possible activity of this radiant is April 3rd. Forty members of this association satisfy the conditions of the Chelyabinsk’s class, see Tab. 6.

In November 2005, Hayabusa spacecraft landed on the asteroid 25143 Itokawa. It captured the dust particles which were analyzed in details. In Nakamura et al. (2011) the authors wrote: "Mineral chemistry indicates that the majority of regolith surface particles suffered long-term thermal annealing and subsequent impact shock, suggesting that Itokawa is an asteroid made of reassembled pieces of the interior portions of a once larger asteroid." Following this ascertainment, Ohsuka et al. (2011) made a search for meteoroids originating from this NEA. As a result, they found that the fireball MORP 172° shows dynamical similarity to Itokawa. Using the Opik variables $U, \cos(\theta)$, (see e.g. Valsecchi et al. 1999) they claim about "a strong dynamical relation (thus genetic) between Itokawa and MORP 172°." Thus, our finding concerning, the Itokawa association, is consistent with Nakamura et al. (2011) and Ohsuka et al. (2011) ascertainment.

4.5 (65803) Didymos association

Didymos group ($\rho_2/309$) was by $D_H$, and $\rho_2$ functions; 20, 70 members respectively. One of the most massive objects in the group is Didymos (65803), $H=17.98^\text{m}$, size 800 [m]. Seventy members of the group were identified by $\rho_2$ function and $D_s=0.056566$. The list of asteroids of Didymos association is given in Table 7, their orbits are illustrated in Fig. 8.

The minimum, maximum and mean Earth MOIDs of this group are: 0.000293 [au], 0.11116 [au], 0.02112 [au], respectively. The smallest one equal to 0.114027 [LD] is found for 2016WQ1, $H=27.89^\text{m}$. Theoretical geocentric radiant parameters of this object are $\alpha_G=284^\circ$, $\delta_G=-22^\circ$ and $V_G=7.63$ [km/s], the date of possible

The fireball photographed by the Canadian Meteorite Observation and Recovery Project.
activity of the radiant is November 18th. Thirty one members of this group fulfill the Chelyabinsk’s class conditions.

4.6 (225312) Cyclids-SEAs association

The name Cyclids for the NEAs association we adopted from Southworth & Hawkins (1963) who first found among the Super-Schmidt photographic meteoroid data a group of five orbits very similar to that of the Earth’s orbit. This discovery was confirmed using larger photographic sample by Lindblad (1971) and Jopek et al. (1999b) and using TV data by Jopek & Froeschlé (1997). Southworth and Hawkins indicated, that the Cyclids are quite probably not a meteoroid stream, e.g. their radiant activity spread was very large — since April to October.

In our basic search, using $D_H$ and $D_I=0.047215$, a group of 73 NEAs orbits was found very similar to that of the meteoroid Cyclids. Our association is consistent with the group mentioned in Chyba (1993) and Rabinowitz et al. (1993). The authors reported an overabundance of the NEAs moving on the orbits similar to the Earth trajectory and called them small-Earth approachers (SEAs). Rabinowitz et al. (1993) state that ‘most of these SEAs have a diameter $d<50$ [m] and are on low-eccentricity, low-inclination orbits and semi-major axis not too deviant from unity’. The sample of SEAs led Rabinowitz et al. (1993) to suggest there is a near-Earth asteroids belt, whose most members have not been detected yet. Brasser & Wiegert (2008) selected 13 SEAs and studied their dynamical evolution and calculated their impact probability with Earth. It emerged that, except of 3, all remaining SEAs have impact probabilities much higher than typical NEA, by up to two orders of magnitude.

Cyclids association were found in our previous studies described in Jopek (2011b.a). Using Southworth & Hawkins (1963) $D_{SI}$ function, and $D_V$ function defined in Jopek et al. (2008) we found two Cyclids like groups, (see Table 8 in Jopek 2011b) which partly entered into our Cyclids-SEAs group of 73 members. Overlooking the distributions of the longitudes of perihelion ($\pi = \Omega + \omega$) we see that the $\pi$-distribution of Cyclids-SEAs differs clearly from that of e.g. the Toutatis group, see Fig. 9. For Cyclids-SEAs, the orientation of the orbit in the plane of motion should be considered as less significant. This reflection encourages us to be less restrictive applying the $D_H$ function. Therefore, we carried out one more search with a bit higher threshold, namely with $D_I = 0.0502$. As a result we identified a group of 129 Cyclids-SEAs ($D_{HI955}$). The names of the members of this association are listed in Table 8. The association ($D_{HI955}$) comprises: 13 Atens, 96 Apollos and 20 Amors; among which we found 29 of the Chelyabinsk’s class. The mean MOID value equals 0.015817 [au], the smallest one amounts to 0.000058 [au] (0.022572 [LD]) and the greatest amounts to 0.159817 [au]. The theoretical radiants of this group occupy a big part of the celestial sphere. Their potential activities are possible all year long.

Among our Cyclids-SEAs we found 6 of 13 ones listed in Brasser & Wiegert (2008), however it should be noted that, to select the SEA, Brasser & Wiegert (2008) used the criteria:
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Figure 10. The plots of the orbits of Cyclids-SEAs association. At the top, 45 orbits observed before AD 2012, at the bottom, 84 orbits observed during the period 2012 – 2019.

Table 8. Cyclids-SEAs (225312) association. 129 members were identified by $D_H$ function, a single linkage cluster analysis algorithm and the orbital similarity threshold $D_t=0.0502$. In bold the names of 29 of the Chelyabinsk’s class are listed.

| Number | Date   | Name               | Type  | Size (m) | Brightness (m) |
|--------|--------|--------------------|-------|----------|----------------|
| 225312 | 1991VG | 2000SG344          | 2001GP2 | 2011Q142 |
| 2003SM84 | 2004EO20 | 2004WH1        | 2006Y26 | 2006Y16   |
| 2006RH120 | 2006Q216 | 2007FF15         | 2007VJ12 | 2006CM14 |
| 2006EA9 | 2008UL34 | 2009TX3        | 2009DB43 | 2009DB55 |
| 2006UA6 | 2008C1      | 2009AO148      | 2010AA37 | 2010AA57   |
| 2013ED12 | 2013BP34 | 2013YB20       | 2012BB14 | 2012BP19 |
| 2013MM55 | 2013RB45 | 2013YY20       | 2015LU17 | 2015LU17 |
| 2015MA96 | 2015LE7    | 2013BB34       | 2013YY20 | 2014CH13 |
| 2014HE197 | 2014KD45 | 2014PY20       | 2014YD  | 2015DU     |
| 2013W400 | 2014WV20 | 2014YD          | 2015DU  | 2015SU     |
| 2015KD57 | 2015PP57   | 2015PP82       | 2015TD55 | 2015TD55 |
| 2015VQ142 | 2015XG878 | 2016CF137      | 2016GL135 | 2016GL222 |
| 2016BR38 | 2016TR119  | 2016TP14       | 2017TP4  | 2017TP4    |
| 2017RP2 | 2017RO30   | 2017SC30       | 2017SC30 | 2017TP9    |
| 2017TH10 | 2017TH10   | 2017TP9        | 2017TP9  | 2017TP9    |
| 2017TK14 | 2017TP14   | 2017TP4        | 2017TP4  | 2017TP4    |
| 2018C14 | 2018CD17   | 2018CD17       | 2018CD17 | 2018CD17   |
| 2018CF14 | 2018CF14   | 2018CF14       | 2018CF14 | 2018CF14   |
| 2018CN5 | 2018CN5    | 2018CN5        | 2018CN5  | 2018CN5    |
| 2018DN1 | 2018DN1    | 2018DN1        | 2018DN1  | 2018DN1    |
| 2018EF2 | 2018EF2    | 2018EF2        | 2018EF2  | 2018EF2    |
| 2018FG1 | 2018FG1    | 2018FG1        | 2018FG1  | 2018FG1    |
| 2019GK3 | 2019GL1    | 2019GL1        | 2019GL1  | 2019GL1    |

Figure 11. 58 orbits of the 1994GV association were identified using $D_H$ function and $D_t=0.047529$. At the top, 23 orbits observed before AD 2012, at the bottom, 35 orbits observed during the period 2012 – 2019. The potential bolide activity of this group ranges from February, 2nd to April, 14th.

Also among our Cyclids-SEAs we discovered all 5 members of the C3 group identified by Schunová et al. (2012). We do not consider the Cyclids-SEAs group as a family of NEAs. We simply report that in our study all members of C3 group belong to the most numerous association.

4.7 Association 1994GV

This group ($D_H/2834$) was found with $D_H$ and $D_t=0.047529$; 58 orbits resemble those of meteoroid stream (see Fig. 11). Using $\rho_1$ metric only 4 NEAs proved to be the members of this group. The MOIDs of the orbits amount to 0.000420, 0.027421, 0.156182 [au] — the minimal, mean and maximal, respectively. The smallest MOID in mean Lunar distance 0.163452 [LD]) was found for 1994GV ($H=27.35^m$, size 11 [m]), the radiant parameters of this asteroid are: $a_G=69^\circ$, $\delta_G=24^\circ$ and $V_G=8.41$ [km/s], the date of possible activity is April, 14th. The most massive member of this association is 2012XY6, its absolute brightness and size amount to 19.09$m$, 500 [m]. The names of the members of this associations are quoted in Table 9; 34 of them belong to the Chelyabinsk’s class.
Table 9. Association 1994GV. 58 members were identified by $D_J$ function and a single linkage cluster analysis algorithm. 34 members printed in bold are of the Chelyabinsk’s class.

| 1994GV | 2007BC8 | 2007BZ48 | 2008CF | 2008FW5 | 2008FL7 |
|--------|---------|---------|--------|---------|---------|
| 2008GE128 | 2009BA11 | 2009BG81 | 2009CD2 | 2009CV5 | 2009DN45 |
| 2009DW | 2009FQ | 2009FR | 2009GL6S | 2011BE24 | 2011BV10 |
| 2013CF6 | 2011FQ16 | 2012DV32 | 2012FQ52 | 2012GR114 |
| 2012X6 | 2013D9 | 2013GR | 2013GD55 | 2014CB13 | 2014GD21 |
| 2014HK196 | 2014IZ164 | 2015AZ13 | 2015CQ13 | 2015CS | 2015DD34 |
| 2015EF | 2015FX35 | 2015HJW11 | 2016CB138 | 2016C330 | 2016CD2 |
| 2016GF1 | 2016GL134 | 2017KX6 | 2018NC3 | 2018NG3 | 2018HC2 |
| 2018FN3 | 2018GN1 | 2018HD1 | 2018XQ4 | 2019BD3 | 2019BH3 |
| 2019CP4 | 2019ET2 | 2019GD4 | 2019GS5 |

Figure 12. 38 orbits of (243147) association was identified with $D_J$ function and $D_J = 0.046288$. Possible activities of the radiants of this association range from July, 12th until August, 12th.

Table 10. Association 243147. 38 members were identified by $D_J$ function and a single linkage cluster analysis algorithm.

| 243147 | 436035 | 436094 | 439889 | 2003NB | 2006QB58 |
|--------|--------|--------|--------|--------|---------|
| 2007PQ | 2009MC9 | 2010DR31 | 2011NZ | 2011OC37 | 2011PU |
| 2011PQ | 2012PO17 | 2013D5X3 | 2013OT3 | 2014MK46 | 2014PR62 |
| 2013PQ56 | 2015RXX2 | 2016DN33 | 2016DM58 | 2016HN15 | 2016HE22 |
| 2016MN32 | 2016NW32 | 2016PR11 | 2016RF10 | 2016TF10 | 2016TK1 |
| 2016UX25 | 2017MB4 | 2017RF15 | 2017RT15 | 2018ME7 | 2018PX7 |
| 2018RR3 | 2019ET2 |

4.8 Association (243147)

This group ($D_J = 0.046288$) of 38 NEAs was found with $D_J$ and $D_J = 0.046288$. The dominant body is (243147), its absolute brightness $H = 4.8$ Association (243147)

4.9 Association 1999TV16

The group of 69 NEAs ($p_2/3041$) was found using $p_2$ distance function and the threshold $D_J = 0.056485$. The 1999TV16 is a small object of diameter 90 [m] and absolute magnitude $H = 23.40^m$. Fig. 13 presents two plots of the orbits of this group, one for 27 objects discovered before AD 2012 and for 42 objects discovered since 2012. It is easy to agree that the drawings represent the same asteroid stream. The orbits approach the Earth’s orbit quite closely, the minimal, mean and maximal MOIDs are 0.000031, 0.02011 and 0.11531 [au], respectively. The smallest MOID (0.012 [LD]) corresponds to 2008TC3, the radiant parameters are $\alpha_G = 348^\circ$, $\delta_G = 8^\circ$ and $V_G = 6.69$ [km/s], the date of possible activity of the radiant is October, 7th. The names of the members are given in Table 11. The asteroid 2008TC3 was a very small 4.1 [m] size object observed only during 1 day in 2008. On October 7th, it entered the Earth’s atmosphere and exploded above the Nubian Desert in Sudan. The impact had been predicted prior to its entry into the atmosphere as a meteor. A few hundred meteors, collectively named Almahata Sitta, were recovered by Peter Jenniskens, with help from students and staff of the University of Kortoum, (see Jenniskens et al. 2009a,b). The case of 2008TC3 shows that the existence of NEAs associations in the surrounding of Earth may be a real threat to its inhabitants.
Table 11. Association 1999TV16. 69 members were identified by \( p_2 \) function and a single linkage cluster analysis algorithm. The group has 24 members fulfilling criteria of the Chelyabinsk’s. Their names are printed in bold.

| 1999TV16 | 2001AV43 | 2003Y70 | 2005WF55 | 2006XQ4 | 2008XY |
|----------|-----------|----------|----------|----------|----------|
| 2006YH2  | 2007DC    | 2007TX22 | 2008TC3  | 2008V8A15 | 2009WM61 |
| 2009BF38 | 2009BH    | 2009UK14 | 2009WK1  | 2009WV7  | 2010AR1 |
| 2010DL   | 2010XW21  | 2010X5C  | 2010XF64 | 2010XG64 |          |
| 2011B10  | 2012BA21  | 2012XW38 | 2012XWN134 | 2013AC3 |          |
| 2012AC53 | 2013AV40  | 2013XV40 |          | 2014AE20 |          |
| 2015CV1  | 2014CV2   | 2014CV6  | 2014CV60 |          |          |

| 2017KR8  | 2017YE4   | 2018B65  | 2018XV1  |          |          |
| 2018XV1  | 2019CV1   |          |          |          |          |
| 2019CR1  | 2019CV2   |          |          |          |          |

Table 12. Association 2000BH19. 30 members were identified by \( p_2 \) function and a single linkage cluster analysis algorithm. 16 members fall into the Chelyabinsk’s class.

| 2000BH19 | 2003XY    | 2006AH4   | 2006GMS3  | 2009F5   | 2010X569 |
|----------|-----------|-----------|-----------|----------|-----------|
| 2011SC55 | 2013PRD3  | 2013V406  | 2014J22   | 2014RU23 | 2014WF6   |
| 2014YD15 | 2015FU444 | 2015XV38  | 2016CWS46 | 2016XA   | 2016XK    |
| 2016XV1  | 2017SN92  | 2017XH13  | 2018BE3   | 2018FL19 | 2018GV3   |
| 2018UF3  | 2018UJ1   | 2018XY6   | 2018XWE   | 2018AB5  |          |

4.10 Association 2000BH19

The group of 30 orbits (\( p_2/3065 \)) was found with \( D_H \) and \( p_2 \) functions, the thresholds were 0.045382 and 0.054300, respectively. The dominant member 2000BH19, is of an absolute magnitude \( H = 19.36^m \), and diameter 400 [m]. The orbits resemble a compact meteoroid stream, see Fig. 14. The minimal, mean and maximal MOIDs of this group are: 0.000280, 0.022864, 0.157994 [au]. The smallest MOID, 0.108968 [LD], we found for 2018FL29, \( H = 30.07^m \). Theoretical radiant parameters of this object are \( \alpha_G = 38^\circ, \delta_G = 15^\circ \) and \( V_G = 11.91 \) [km/s], the date of possible activity is November, 21st. The list of the association members is given in Tab. 12. 16 members are of the Chelyabinsk’s class.

4.11 Association 523606

Using \( D_H \) function and \( D_T = 0.049453 \), 8 members of (523606) association were identified. Similar result was obtained with \( p_2 \) and \( D_T = 0.044688 \), 11 objects were found. However, using \( p_1 \) and \( D_T = 0.049453 \), 24 NEAs were classified as an association (\( p_1/2710 \)). The asteroid (523606) is the brightest and the biggest object in this group, \( H=20.23^m \), \( D = 300 \) [m]. The spatial distribution of the orbits of this cluster resembles a meteoroid stream, see Fig. 15. All orbits approach the Earth’s orbit closer than 0.05 [au] (PHA limit); the minimal, mean and maximal MOIDs are: 0.000049, 0.019069, 0.026283 [au]. The smallest MIOID we found for 2018UA, \( H = 30.15^m \). Theoretical radiant parameters of this object are \( \alpha_G = 354^\circ, \delta_G = 18^\circ \) and \( V_G = 11.92 \) [km/s], the date of possible activity is October, 20th. In [LD] unit 2018UA MIOID = 0.019069, which equals 1.15 of the Earth radius.

Table 13. Association 523606. 24 members were identified by \( p_3 \) function and a single linkage cluster analysis algorithm. 14 NEAs, printed in bold, belong to the Chelyabinsk’s class.

| 523606  | 1993T2Z  | 2003SS84 | 2006BN26 | 2007CF8  | 2007TUS  |
|---------|----------|----------|----------|----------|----------|
| 2007VY14 | 2009UL28 | 2009XW77 | 2010BD1  | 2012CO2  | 2013BR74 |
| 2013UK1  | 2014SC32 | 2015BP13 | 2016X21  | 2017PA4  | 2017TH5  |
| 2017TIZ3 | 2017U4U  | 2018BQS  | 2018UV5  | 2018VBR1 |

Figure 15. 24 orbits of (523606) association were identified with \( p_3 \) function and \( D_T = 0.049453 \). The potential bolide activity of this group ranges from October 9th, to January 13th.

Table 14. Association 2000SE8. Twenty objects were found with the \( p_1 \) function and \( D_T = 0.048284 \) (\( p_1/3137 \)). The NEAs of this group are rather small objects; one of the dominant members is 2000SE8 of an absolute magnitude \( H=22.89^m \), and size 60 [m]. The orbits resemble a meteoroid stream, see Fig. 16. The minimal, mean and maximal MOIDs of this group are: 0.000257, 0.045534, 0.129974 [au]. The smallest MIOID (0.10017 [LD]) we found for asteroid 2015SG, \( H=26.43^m \). Theoretical radiant parameters of this object are \( \alpha_G = 232^\circ, \delta_G = -21^\circ \) and \( V_G = 7.77 \) [km/s], the date of possible activity is September, 5th. The list of members of the group is given in Table 14, a half of them are of the Chelyabinsk’s class.
Table 14. Association 2000SE8. 20 members were identified by $\rho_1$ function and a single linkage cluster analysis algorithm. In bold the names of the Chelyabinsk’s class objects are given.

| 2000SE8 | 2007KR17 | 2009SM1 | 2010RB130 | 2010RC31 | 2010RQ64 |
|---------|----------|---------|-----------|----------|----------|
| 2011OE  | 2011QH50 | 2014SS1 | 2015Ro35  | 2015RZ56 | 2015SG   |
| 2016E52 | 2016QR   | 2016PG  | 2016V19   | 2017PD25 | 2017QS32 |

4.3. Association 1999YD

Exactly the same result we obtained when using the $D_H$ and $\rho_1$ functions, 11 orbits of this association ($D_H/3058$) were found with the thresholds $0.037268$ and $0.043102$, respectively. The largest member of this group is 1999YD, $H = 21.12^{m}$, size 200 [m]. The association clearly resembles a compact meteoroid stream, see Fig. 17. The orbits approach the Earth orbit closely, the minimal, mean and maximal MOIDs are: 0.000342, 0.032855, 0.083527 [au]. The smallest MOID (0.133096 [LD]) we found for 2007YM, $H = 26.06^{m}$. Theoretical radiant parameters of this object are $\alpha_G = 351^{\circ}$, $\delta_G = -9^{\circ}$ and $V_G = 8.34$ [km/s], the date of possible activity is November, 21st.

Table 15. Association 1999YD. 11 members were identified by $D_H$ and $\rho_1$ functions and a single linkage cluster analysis algorithm. 6 NEAs fulfill criteria of the Chelyabinsk’s class.

| 1999YD  | 2000SW10 | 2001UW5 | 2004YE | 2007YM | 2008UT5 |
|---------|----------|---------|--------|--------|---------|
| 2009YY3 | 2016WV2  | 2017UT5 | 2018T5 | 2018VQ6| 2016WV2 |

4.4 Association 1996GQ

The group consists of 10 orbits, it was found using the $\rho_1$ function and $D_r = 0.043102$, only (internal code is $\rho_1$ [2870]). The brightness of the asteroid 1996GQ is $23.17^{m}$, and its size equals 210 [m] (albedo 0.024 was assumed). The orbits clearly resemble those of a meteoroid stream, see Fig. 18. The minimal, mean and maximal MOIDs of this group are: 0.008514, 0.062156, 0.134925 [au]. The smallest MOID (3.313396 [LD]) we found for 2009FQ10, $H = 25.51^{m}$. Theoretical radiant parameters of this object are $\alpha_G = 46^{\circ}$, $\delta_G = 11^{\circ}$, $V_G = 6.11$ [km/s] and the date of possible activity is February, 13th.

Table 16. Association 1996GQ. 10 members were identified by $\rho_1$ function, $D_r = 0.043102$, and a single linkage cluster analysis algorithm. In bold 3 asteroids are printed which fulfill criteria of the Chelyabinsk’s class.

| 1996GQ  | 1996GQ10 | 2012FQ52 | 2013DX | 2014ES3 | 2016CY99 |
|---------|----------|----------|--------|---------|----------|
| 2016D2 | 2017BL123 | 2017EJ4 | 2019CT | 2016CY99 |

4.5 Association 2014FW32

The group (2014FW32) consists of 6 orbits, it was found using the $\rho_1$ and also $\rho_2$ function, the thresholds were $D_r = 0.037021$ and $D_r = 0.036307$. The NEA 2014FW32 absolute magnitude is 26.98 [m] and its diameter is 15 [m]. The orbits resemble those of a meteoroid stream, see Fig. 19, similar to Cyclids-SEAs association, however all the orbits are within the Earth’s orbit. All 6 members belong to the Aten group. The minimal, mean and maximal MOIDs of this association are: 0.000702, 0.007543, 0.015019 [au]. The smallest MOID (0.273198 [LD]) we found for 2015GR4, $H = 27.08^{m}$. Theoretical radiant parameters of this object are $\alpha_G = 328^{\circ}$, $\delta_G = -25^{\circ}$.
and $V_G=2.54$ [km/s], the date of possible activity is March, 11th. The list of members of this association is given in Table 17. Only one asteroid of this group belongs to the Chelyabinsk’s class.

5 CONCLUSIONS

We have made three attempts at extensive and very rigorous search for grouping among 20032 NEAs. Probability of accidental clustering was small, below 1%. Fifteen associations were found using a single linkage cluster analysis algorithm, the same as used by Zappala et al. (1990) in the search for asteroid families among the main belt asteroids (MBA). Zappala et al. called this algorithm as hierarchical cluster analysis algorithm. In our search only 953 orbits (~4.7%) were classified as the association members.

To quantify similarity among two orbits we applied three distance functions: $D_H$, $\rho_1$ and $\rho_2$. Both $\rho$-functions proposed recently by Kholshevnikov et al. (2016) worked well, they gave results comparable with those obtained by $D_H$ function (Jopek 1993b). Hence, in our view, the new functions do not constitute a major breakthrough in the small bodies cluster analysis. However, from the mathematical point of view, they have the obvious advantage — they satisfy three axioms of a metric space. Therefore, they must be applied firstly.

All orbital plots of identified associations clearly resemble the meteoroid streams, see Figures 4–8 and 10–19. However, we do not claim that our associations are of the genetic nature, i.e. that they originated from the common parent bodies. No cluster analysis can prove it. We only claim, that despite of their origin, the identified associations really exist. At the moment no one knows how many NEAs a single group include. Perhaps 70 members, but perhaps it contains 700? We showed that the number of members identified in the association increases with time, as we have found for Anza, Zephyr, Toutatis, Itokawa and other large groups. This fact is important if the probability of the collision between the Earth and the NEAs is to be calculated. A hazard to the Earth and its inhabitants is very serious. Among the members of the identified associations we found many members, on average 34%, that are larger than the Chelyabinsk object and that approach the Earth orbit at a distance smaller than 0.05 [au]. Two asteroids belonging to the associations approached the Earth orbit extremely closely, at distances smaller than the Earth radius: 2017FU102 a member of the Itokawa association and 2008TC3 a member of 1999TV16 association. The latter object entered the Earth atmosphere on October 7, 2008 and exploded at ~37 [km] above the Nubian Desert in Sudan, (Jenniskens et al. 2009b).

The common origin of the members of the identified groups is an open question. They could arise as a result of collisions (e.g. Itokawa and Toutatis associations) or could be a result of migration processes induced by some dynamical resonances. Further investigation is needed on the number and the nature of the NEAs associations.

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Figure 19. The group of 6 orbits of 2014FW32 association were identified using $\rho_1$ and $\rho_2$ functions. The orbits resemble Cyclids-SEAs association and are located inside the Earth’s orbit (the biggest ellipse in black colour).
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