Mem. S.A.It. Vol. 82, 310

Memorie della

Meteoroid streams and their parent bodies

T. J. Jopek

Institute Astronomical Observatory, A. Mickiewicz University ul. Sloneczna 36, PL-62-286 Poznań, Poland, e-mail: jopek@amu.edu.pl

Abstract. Various points concerning meteoroid streams and their parent comets and asteroids are presented. The first connection between meteoroids and comets, among others, were established by G.V. Schiaparelli 150 years ago. The first computer search for meteoroid streams was made by Southworth and Hawkins 50 years ago. Since that time many investigators have been studied the problem of cometary and asteroidal origin of meteoroid streams. Many results have been established. In this study we made the most extensive search for streams and their parent bodies amongst photographic meteoroids, comets and minor planets. We used two D- distance functions and rigorous cluster analysis approach. The well known results have been confirmed — several major streams and their parents have been identified. Also we found ten associations consisting mainly of the near Earth asteroids. The obtained results do not allow us to make a final conclusions about the genetic reality or the origin of these associations.

Key words. meteors - meteoroid - meteoroid streams - parent bodies of the meteoroid streams - asteroidal streams - stream searching techniques

1. Introduction

Similarity between the cometary and meteoroids orbit were discovered by several authors between 1860 and 1870 AD. Pape (1861), Weiss (1867) and Galle (1867) established that a close similarity existed between the orbit of comet 1861 I and that of the Lyrid meteors. Schiaparelli (and after Olivier 1925 and Lovell 1954) established a connection between the Perseids and comet 1862 III, and the Leonids and comet 1866 I. The investigators mentioned above assumed that the Lyrid and Perseid meteroids moved on parabolic orbits. For the Leonids, Schiaparelli was able to compare all orbital elements. For the next fully determined meteoroid orbits we had to wait several decades, until Fred Whipple started a first successful photographic double station observations of meteors. It turned out that many meteoroids moved on short periodic orbits, and some of them are very similar to the orbits of short periodic comets. As a result, a similarity between the orbits of the Taurids and comet Encke was noted. The cometary origin of meteoroids was accepted beyond doubt, in particular, after the paper by Whipple (1951), in which the author introduced a dirty-snow ball cometary model. Whipple has shown that meteoroids (large cometary dust grains) are carried away from the comet nucleus as a result of the gas production process.

Due to obvious reasons, the asteroidal origin of meteoroids was not postulated before 1898, till the first near Earth asteroid - 433 Eros was discovered. Possible associations between the meteoroid showers and asteroids were mentioned by Olivier (1925). Whipple (1938) and Hoffmeister (1937, 1948) suggested several associations, e.g. between the Virginids and 1862 Apollo, the Piscids and 69230 Hermes, the Scorpio-Sagittariids and 2101 Adonis. However, none of these propositions survived more rigorous testing. In case of asteroids, we need another mechanism to produce meteoroid streams. Collisions producing craters can eject dust from the asteroid. However such a process can't eject enough dust to form a strong meteor shower, and it is not a regular, periodic event. Destructive collisions between two big bodies, forming asteroid families, might be an efficient process for the formation of meteoroid streams. But such collisions are very rare, and because all known such events happened a long time ago, meteoroid streams resulting after them had enough time to disperse[1]. Recently, two additional processes for the formation of an asteroidal meteoroid stream were proposed. In Veres et al. (2008) the authors consider a tidal splitting of the asteroid regolith due to a close encounter with planets. The second one is based on the Yarkovsky-O'Keefe-Radzievski-Paddack (YORP) effect — induced spin-up and rotational fission of fast rotating objects (see e.g. Pravec et al. 2010).

Except for the cometary ejection, all mechanisms above have weak points: they are not regular, or are they not sufficiently efficient. However, it is possible that a regular and efficient process for the formation of meteoroid streams format is not needed. As suggested several years ago, many NEAs have a cometary nature, therefore they may be considered as dormant comets (see Jenniskens (2008a,b)).

With the years, the number of orbits in the catalogs of comets, asteroids and meteoroids increased. At the same time, with the advent of computers, searching for meteoroid streams and their parent bodies proved to be a not so tedious work as it was at the time of e.g. Whipple (1954) and Terentjeva (1967), who were searching for similar orbit by "eyes".

The computer detection technique has been introduced by Southworth and Hawkins (1963). After their study, many investigators used computers to identify meteoroid streams and in studies on genetic affinity among meteoroids, asteroids and comets (Nilsson 1964; Lindblad 1971a,b, 1974, 1992, 1994; Sekanina 1970a,b, 1973, 1976; Gartrel and Elford 1975; Drummond 1981, 1991, 2000; Jopek 1986, 1993b; Jopek and Froeschlé 1997; Jopek et al. 1999a,b, 2003, 2008, 2010; Olsson-Steel 1988; Porubčan et al. 1991; Porubčan and Gavajdova 1994; Kostolansky 1998; Galligan and Baggaley 2002b; Galligan 2003; Brown et al. 2008; Jenniskens 2008a)

In this study we have made a similar search, however using significantly larger orbital sets of the photographic meteoroids, NEAs and comets.

2. Searching for meteoroid streams and their parent bodies

To classify meteoroid into streams and to find their parent bodies one needs a meteoroid stream definition. The definition based on the common origin — the stream consist of particles ejected from the same parent body — is useless from a point of view of practical implementation.

Therefore in practice a meteoroid stream is defined by the identification procedure, for which three essential components are necessary: (1) a distance function i.e. a measure of dynamical similarity among two meteoroids, (2) a similarity threshold value, (3) and a cluster analysis technique. Southworth and Hawkins (1963) were the first who introduced the distance function D_{SH} named D-criterion. Drummond (1981) gave its modification D_D and Jopek (1993a) proposed an alternative hybrid D_H. All D- functions measure distances in the five-dimensional orbital elements space e, q, ω, Ω, i.

Further variations of the original D_{SH} function were given in Steel et al. (1991), Asher et al. (1993), where instead of five-dimensional space the authors use only three-dimensions

[1] We know only one exception. At the end of January 2010, Jewitt et al. (2010) observed an object (P/2010 A2) of complex structure that suggests the object is not a comet but instead the product of a head-on collision between two asteroids.

q, e, i or a, e, i. Valsecchi et al. (1999) introduced a new D_N function involving four quantities $U, \cos\theta, \phi$ and λ; first three borrowed from Öpik's theory of close encounters (Öpik , 1976): the geocentric velocity U, and the angles θ, ϕ defining the anti radiant direction in the geocentric ecliptic rotating reference frame located at the longitude λ at the time of the meteor observation.

Recently, yet two another distance functions were proposed: D_B by Jenniskens (2008a) defined in terms of three dynamical quasi-invariants, and D_V by Jopek et al. (2008) where the authors applied the heliocentric vectorial elements. Kholshevnikov and Vassiliev (2004) gave completely different proposition: the authors considered a Keplerian ellipse as a point in the five dimensional space of orbits, and as a metric they proposed *natural* metric of Hölder type.

Having both, the distance function and the similarity threshold D_c, a meteoroid stream can be detected by suitable cluster analysis algorithm. Including $D-$ function and the similarity threshold, the cluster analysis algorithm defines a meteoroid stream. Several definitions were proposed in the past, in all cases a stream is considered as a group of meteoroids for which a significant concentration of dynamical parameters is observed. According to the simplest definition, a meteor stream consists of orbits concentrated around the adopted mean one. Sekanina (1976) and Welch (2001) introduced some iterative variation of this method. Another definition is realized as a cluster analysis algorithm based on a single neighbour linking technique (see Southworth and Hawkins (1963)). A different approach, the method of indices, was proposed by Svoreň et al. (2002). Galligan and Baggaley (2002a) and also Brown et al. (2008) identified meteor streams using the wavelet transform technique.

We have many methods for meteor stream searching, but there are still several open problems: which cluster analysis method is the best for a given meteoroid sample? What is the optimal way to find the threshold of dynamical similarity? What dynamical parameters should one use for this purpose? They are difficult problems, already studied by several investigators (Štohl and Porubčan , 1987, 1991; Galligan , 2001; Neslušan and Welch , 2001; Rudawska , 2010). At the moment we don't have satisfactory answers to these questions.

3. Orbital data and the method used in this study

3.1. Orbital data

We used 4097 photographic meteors extracted from the computer files `geo2003.dat` and `orb2003.dat` downloaded from the IAU Meteor Data Center (Lindblad et al. 2003). Before using them for the classification, the 4581 meteor data available were examined with a slightly different method from those described in Jopek et al. (2003) to check their internal consistency. The test failed 306 times, and all these data as well as the orbits with $e > 1.1$ were rejected.

The 4097 meteoroids have been supplemented by one bolide orbit obtained from Trigo-Rodríguez (2008, priv. comm.), and by 5518 NEAs orbits and 579 cometary orbits. The NEA data were taken from the NeoDys website (updated to spring 2008). The cometary orbits were selected from Marsden and Williams (2003) catalogue; except for comet Biela, only single apparitions and the orbits with eccentricity $e < 1$ were selected. We have also included the orbit of comet 169P/NEAT.

3.2. Searching method

As a quantitative measure of the difference between two orbits we have used two distance functions: D_{SH} introduced in Southworth and Hawkins (1963) and D_V introduced in Jopek et al. (2008). First, the set of 10195 objects was pre-classified (using a single neighbour linking technique, D_{SH} function and a rough estimate of the threshold) and the sporadic sample (almost grouping free) of 4450 objects was obtained. Using this sample, the threshold of the dynamical similarity for each distance function was found with a method similar to that used in Jopek and Froeschlé (1997); Jopek et al. (1999a, 2003). However, instead of determining the thresholds with a single numerical experiment as in our previous works, ten of these were carried out, each repeated 200 times. The average values of the thresholds and their standard deviations are listed in Table 1. Next, using these thresholds and a single neighbour linking technique, we processed all 10195 objects accepting all groups of 5 or more members detected with the reliability level 99%.

4. Results and discussion

The main results are presented in the second and third columns of Table 2. The last four columns list the results obtained with $D_{c,M} \pm \sigma_{D_{c,M}}$, the upper and lower boundary of the thresholds intervals, respectively (see Table 1). In all basic searches (cols 2-3 of Table 2) about 18-25% of the sample turned out to belong to the stream component. Here by "stream" we mean a group of objects which includes meteoroids, comets and the NEAs. Three searches with the D_{SH} function gave very similar result. For the D_V function four streams, identified as separate groups with $D_{c,M}$, were connected in complex groups when the thresholds $D_c + \sigma_{D_{c,M}}$ were applied. In what follows we present the results in a more detailed way.

4.1. Major meteoroid streams and parent bodies

In Table 3 a first set of results obtained with D_{SH} and D_V is given. The results are quite consistent and they agree with the results already known from the literature.

Perseids: The Perseids were identified by both D-functions as the most numerous stream in the orbital sample studied. Also their parent body has been identified — 109P/1992 S2, the comet Swift-Tuttle.

Geminids: With D_{SH} we found 381 Geminids; a very similar amount (371) was found using the D_V function. In both searches, the NEA '3200', Phaethon, was included as a member of the meteoroid stream identified.

Orionids and η Aquariids: The twin stream Orionids and η Aquariids, and their parent comet Halley (1P/1982 U1), were found by both functions: with D_{SH} we found 62 Orionids and 13 η Aquariids, while with D_V we found 44 Orionids and 11 η Aquariids.

Quadrantids: Using D_{SH} we found 52 Quadrantids, however no parent body was identified. With D_V, we detected 49 meteoroids and one parent body — the asteroid 2003EH1. When the basic search was repeated using the D_c thresholds corresponding to a 95% reliability level, the results were the same, except

Table 1. Values of the thresholds $D_{c,M}$ and their uncertainties $\sigma_{D_{c,M}}$ applied in the association tests to 10195 orbits. The thresholds correspond to the reliability level 99% and are given for each group of M members and for each D-function: D_{SH}, D_V

	$D_{cM} \pm \sigma_{D_{cM}}$			
M	D_{SH}		$D_V \cdot 10^{-2}$	
2	0.0224	± 0.0032	0.0058	± 0.0003
3	0.0293	± 0.0025	0.0090	± 0.0002
4	0.0355	± 0.0019	0.0118	± 0.0002
5	0.0412	± 0.0014	0.0144	± 0.0002
6	0.0462	± 0.0010	0.0167	± 0.0002
7	0.0508	± 0.0007	0.0187	± 0.0002
8	0.0548	± 0.0005	0.0205	± 0.0002
9	0.0584	± 0.0005	0.0221	± 0.0002
10	0.0615	± 0.0006	0.0235	± 0.0002
11	0.0642	± 0.0006	0.0247	± 0.0002
12	0.0666	± 0.0007	0.0256	± 0.0002
13	0.0685	± 0.0007	0.0265	± 0.0002
14	0.0702	± 0.0007	0.0272	± 0.0002
15	0.0716	± 0.0007	0.0277	± 0.0002
16	0.0727	± 0.0007	0.0282	± 0.0001
17	0.0736	± 0.0006	0.0285	± 0.0001
18	0.0743	± 0.0006	0.0287	± 0.0001
19	0.0748	± 0.0006	0.0289	± 0.0001
20	0.0752	± 0.0005	0.0291	± 0.0001
21	0.0755	± 0.0005	0.0291	± 0.0001
22	0.0757	± 0.0005	0.0292	± 0.0001
23	0.0759	± 0.0005	0.0293	± 0.0001
24	0.0761	± 0.0005	0.0293	± 0.0001
25	0.0762	± 0.0005	0.0294	± 0.0001
26	0.0765	± 0.0005	0.0295	± 0.0001
27	0.0767	± 0.0005	0.0297	± 0.0002
28	0.0772	± 0.0004	0.0299	± 0.0002
29	0.0777	± 0.0004	0.0303	± 0.0002
30	0.0784	± 0.0004	0.0307	± 0.0002

Table 2. General results of six searches for meteoroid streams and their parent bodies; S and P_S are the number of streams and the fraction of stream component detected in this study. The results were obtained using thresholds equal to D_{cM}, $D_{cM} - \sigma_{D_{cM}}$ and to $D_{cM} + \sigma_{D_{cM}}$; columns 2-3, columns 4-5, and columns 6-7 respectively.

	S	P_S [%]	S	P_S [%]	S	P_S [%]
D_{SH}	21	17.9	21	17.6	21	17.9
D_V	23	25.4	23	25.0	19	25.7

Table 3. Major and minor meteoroid streams and their parent bodies detected in two searches. The first column gives the stream name, the second its IAU shower code, the third and fifth ones the number of meteoroids (N_M) identified by D_{SH} and D_V functions. The parent bodies identified in each search are given in columns fourth and sixth. In case of D_V, the Dec. Monocerotids and their parent comet were identified with $D_c = 0.0288 \cdot 10^{-2}$ which corresponds to the reliability level 95%.

Meteoroid	IAU	D_{SH}		D_V	
	Code	N_M	P. body	N_M	P. body
Perseids	PER	641	109P/1992 S2	631	109P/1992 S2
Geminids	GEM	381	'3200'	371	'3200'
Orionids	ORI	62	1P/1982 U1	44	1P/1982 U1
η Aquariids	ETA	13	1P/1982 U1	11	1P/1982 U1
Quadrantids	QUA	52		49	'2003EH1'
Leonids	LEO	28	55P/1997 E1	3	
				15	55P/1997 E1
Dec. Monocerotids	MON	13	C/1917 F1	12*	C/1917 F1
Lyrids	LYR	13	C/1861 G1	2	C/1861 G1
				3	
κ Cygnids	KCG	36	-	24	-
(S) δ Aquariids	NDA	41	-	16	-
(N) δ Aquariids	SDA	9	-	-	-

that 50 Quadrantids were identified with the D_V function.

Leonids: The Leonids are not well represented in the orbital sample studied: all were observed between 1950 and 1991, i.e. before the high activity of this stream at the break of the XX and XXI centuries. We found 28 members with D_{SH} and 18 with D_V, but with this latter in a form of two branches, 15 and 3 meteoroids. In both cases the parent body 55P/1997 E1, comet Tempel-Tuttle was detected.

December Monocerotids: With a reliability level of 99%, 13 members of Dec. Monocerotids stream and their parent comet Mellish (C/1917 F1) were found with the D_{SH} function. To obtain similar results with D_V, thresholds corresponding to the 95% reliability level had to be used, and we detected 12 Monocerotids and the same parent comet.

Lyrids: Using D_{SH} we found 13 Lyrids; with D_V, the stream was less numerous, only 5 members were detected forming two branches. In both searches the same parent body was identified — the comet Thatcher (C/1861 G1).

κ Cygnids: With D_{SH} we found 36 κ Cygnids and 24 with D_V. No parent body was detected in either searches. Using a bit higher thresholds, corresponding to reliability level 95%, 37 κ Cygnids were detected with D_{SH}, and 28 with D_V. However, as previously, no parent body was found. Our result is consistent with the information given for this stream in the database IAU MDC (2007).

N. and S. δ Aquariids: No parent body was found in either search. We found 36 Southern δ Aquariids with D_{SH} and 24 with D_V. 9 Northern δ Aquariids were detected only with D_{SH}.

Table 4. Complex groups of meteoroid streams and their parent bodies detected by D_{SH} and D_V functions. N_M — the number of identified meteoroids; $N_{A/C}$ denotes the number of parent bodies identified among asteroids and comets, respectively.

Meteoroid stream	IAU Code	D_{SH}		D_V	
		N_M	$N_{A/C}$	N_M	$N_{A/C}$
Taurids (S)	STA	14	0/0		
Taurids (N,S)	NTA STA	174	9/0	134	11/1
α Capricornids	CAP	40	2/0	136	647/3
				10	0/1
				26	0/0

4.2. Complex meteoroid streams

In Table 4 a second set of results is given, sometimes difficult to interpret. With the method applied in this study, we had difficulties in identifying some groups reliably. Below we discuss the case of the Taurids and α Capricornids.

4.2.1. Taurids Complex

With D_{SH} we found two groups of Taurids. The first of 14 members consisted of Southern Taurids only; no parent body was connected with this group. The second group included 174 Taurids (Northern and Southern branches) and 9 NEA's. With D_V we found 134 Northern and Southern Taurids, and 12 parent bodies: 11 NEA's and one comet. The names of the objects detected in both searches are given in Table 5. Inclusively, 14 parent bodies of the Taurids stream have been detected, 7 of them in both searches. Associations among particular NEA's and Taurids have been found by several investigators, and we confirm some of them (see references in Table 5). However, some associations between Taurids and NEO's were not found in our search, e.g. no association was found between Taurids and minor planets: (4179) Toutatis (Porubčan et al. , 1991); 5055-PL (Olsson-Steel , 1988; Porubčan et al. , 1991; Babadzhanov , 2001); 1984 KB (6063 Jason) (Asher et al. , 1993; Porubčan et al. , 1991), and several others listed in Asher et al. (1993); Babadzhanov (2001); Porubčan et al. (2006).

Table 5. The list of parent bodies of the Taurids meteoroid complex detected in this study.

Minor planet	D-function	References
2003 WP21	D_{SH}, D_V	PKW, J08b
2004 TG10	D_{SH}, D_V	PKW, J08a
2005 TB15	D_{SH}, D_V	
2005 UR	D_{SH}, D_V	
2006 SO198	D_{SH}, D_V	
2007 RU17	D_{SH}, D_V	B3W
2007 UL12	D_{SH}, D_V	B3W
2002 MX	D_{SH}	
2003 UV11	D_{SH}	
2201 (Oljato)	D_V	ACS,B1, PSV
2005 NX39	D_V	
2005 TF50	D_V	PKW
2005 UY6	D_V	
2P/Encke	D_V	

ACS: Asher et al. (1993); B1: Babadzhanov (2001); B3W: Brown et al. (2010); J08a,b: Jenniskens (2008a,b); PKW: Porubčan et al. (2006); PSV: Porubčan et al. (1991).

4.2.2. α Capricornids Complex

With D_{SH} we found 40 α Capricornids and two parent bodies: 2002 NW and 2004 BA75. Using D_V and the thresholds given in Table 1, the results proved to be not realistic, possibly due to the limitation of the statistical threshold determination and disadvantages of a single linkage cluster analysis algorithm. With D_V we found a huge group of 136 meteoroids, 647 NEA's and 3 comets. When the thresholds were multiplied by 0.91, we observed that a huge group split into three branches. They were two branches of α Capricornids of 10 and 26 members (34 of them were also found with D_{SH}). The third group of 502 members (mostly NEA's) will be discussed later. With D_V, we found a parent body, the comet 169P/NEAT (previous minor planet 2002EX12) for the smaller branch of the α Capricornids. This result confirms what was already known and discussed recently by Jenniskens & Vaubaillon (2010); Kasuga et al. (2010), who used different methods: evolutional studies and photometric observations, respectively.

4.3. Complex groups of meteoroids, comets and NEAs

The next set of results of our study are given in Table 6 — the groups consisting of comets only, NEAs only, but most of all they are mixed groups in which the main part consists of minor planets. We have met such complicated group in section 4.2.2, which in our opinion wasn't a realistic one. All orbits which belong to complex groups have a very small inclinations, and therefore are strongly perturbed by the planets. Strong orbital dispersion together with significantly higher orbital concentration near the ecliptic add both to complicate searches for realistic grouping among such orbits. Below, we

Table 6. Groups consisting of comets, minor planets and meteoroids detected in this study.

Group name	D_{SH} N_M	D_{SH} $N_{A/C}$	D_V N_M	D_V $N_{A/C}$
Bielids	2	0/7	2	0/8
Kreutz group	0	0/6	0	0/8
Shoemaker-Levy	0	0/19	0	0/19
Association 228			5	33/0
Association 694			6	34/0
Association 1821			1	38/0
Association 4266			0	20/0
Association 495	8	19/0	6	27/0
Association 657			5	25/0
Association 177			15	63/0
Association 796	11	25/0		
Association 1612	3	12/0		
Association 43	5	17/0	53	449/0

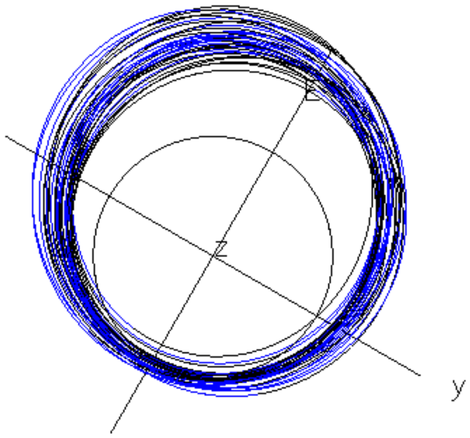

Fig. 1. Association 694 plotted on the ecliptic plane. The orbits have low inclination and remarkably resemble a meteoroid stream. The Earth circular trajectory is seen inside the associating.

present results which, at least partly, we do not consider final.

4.3.1. Cometary groups

This is very obvious result. The catalogue of comets we have used (Marsden and Williams , 2003) contains members of Kreutz group. It also contains the comets that originated from the splitting of the comet Biela and Shoemaker-Levy. Thus, we have identified the members of these groups, which gives a positive evaluation of the searching methods applied in this study.

4.3.2. Asteroidal groups

Asteroidal groups are presented in a second section of Table 6. We included here all groups which contain fewer meteoroids then asteroids. Grouping among the NEA's orbit has been pointed out earlier: in Drummond (1991) the author found three associations among 139 NEA. They included 4-5 members. In Drummond (2000) 14 associations were found with 4-25 members. This time Drummond searched amongst 708 NEAs. However, Drummond estimated that as many as 75% of the groupings found by him might be attributed to chance alignments due to selection effects in the observations.

Association 228. Detected only with D_V. 5 meteoroids inside this group were not classified as stream members in our earlier study (see Jopek et al. 2008), where we have searched the same meteoroid sample. We list in Table 7 the names of 33 minor planets, members of this group. None of these asteroid were found as a group member by Drummond (1991, 2000). When the thresholds from Table 1 were multiplied by 0.91 (more rigorous approach) this group was not identified.

Association 694. We found 6 meteoroids and 34 NEA's in this group only with D_V (Fig. 1). The members of this group were never before classified as a possible association. The orbits of this group are very similar and the group was also detected with a more rigorous approach — 15 members were found, all but one asteroids.

Association 1821. This group found with D_V consists of minor planets mainly (only one meteoroid in this group). It is a new association. Its members were not mentioned in the paper by Drummond (1991, 2000). Using a more rigorous approach the association was not identified.

Association 4266. This group was found with D_V. It is a new group and consists of minor planets only. With a more rigorous approach

Table 7. The names of minor planets — members of the associations listed in Table 6.

Association 228			
1943	20429	141018	1994CJ1
1999NA5	2001YF1	2003CC	2003DW10
2004AE6	2004CZ1	2004HL	2004KG17
2004PJ2	2005EU2	2006AR2	2006DN
2006HX30	2006KL103	2006KS1	2006YC13
2007BD8	2007FY20	2007KK	2007LT
2007LV19	2007MH	2008CC71	2008ED85
2008EG9	2008EQ7	2008GR3	2008HQ3
2008LE			
Association 694			
7480	36017	99799	1997WB21
1998VS	2001QF96	2001SZ169	2001WH49
2001XP88	2002CY58	2002RO28	2003BQ35
2003QU5	2003TK1	2004RW2	2004SU55
2005QA5	2005SD71	2005UN	2005VS
2006SK61	2006SV5	2006UA216	2006UL
2006UN	2006UP	2006WZ184	2007BF72
2007PQ9	2007TA23	2007TT24	2007VV6
2007WZ4	2008PG1		
Association 1821			
171486	1993HP1	1994GV	1999AM10
1999HC1	2001FB58	2001FE7	2002AN129
2002AT4	2002BA1	2003AJ73	2003YP17
2003YR70	2004GD2	2004HT38	2004YK1
2005EZ29	2005GX119	2006AN4	2006BW39
2006DO62	2006DU	2006EE	2006KP21
2006WU	2007BZ48	2007DJ	2007EO
2007FG1	2007FJ1	2008AM33	2008DW22
2008EZ7	2008FE	2008GE128	2008GQ
2008HA2	2008JV2		
Association 4266			
11054	141874	190208	1989UP
1993RA	1993TZ	1999UR	2000WG63
2003SS84	2003UR25	2005TF	2005YV55
2006QR89	2006SY217	2006YH2	2007SV2
2007UF6	2007UT65	2007UU3	2007YR56
Association 177			
3352	5797	7341	8037
24475	27002	31669	37638
52340	162695	162998	168318
1994GK	1994XM1	1998FG12	1998WB2
1998WD31	1998WZ1	2000BH19	2001DS8
2001VJ5	2001WL15	2002YC12	2003BS47
2003XV	2003YP94	2004BF11	2004BN41
2004FY3	2004XH3	2004XK4	2005BD
2005CP7	2005EJ169	2005XO4	2005YY36
2006AH4	2006AU3	2006BA8	2006BY7
2006HD2	2006SJ198	2006SW5	2006VC
2006WM3	2006XZ2	2006YA	2006YB
2006YD12	2006YH14	2007AH12	2007EN88
2007FC	2007GY1	2007SJ	2007VY7
2007XQ3	2008BE	2008CE6	2008CK
2008EL85	2008FK	2008FW6	
Association 43			
2000XF44	2001VD2	2002AE29	2002RB182
2003TO9	2003WY153	2004VZ60	2006XV4
2006XX	2006YP44	2006YR2	2007XN16
2007YY59			

this association was not identified.

Associations 495, 657. Group No 495 was found with D_{SH}, and more in number with D_V. The names of the minor planets in this group identified in both searches are given in Table 8. 11 objects of this group are in the list of 13 SEA's asteroid given by Brasser & Wiegert (2008) (see Table 8). However the authors did not postulate the common origin for these objects. Additionally we found several meteoroid orbits inside this association very similar to the Earth's orbit. Such group of meteoroids called "Cyclids" has been identified earlier by Southworth and Hawkins (1963); Lindblad (1971a); Jopek et al. (1999a).

The second association 657 was detected with D_V only. The orbits of 5 meteoroids and 25 NEA's have small eccentricities and semi-major axes close to 1 AU. They are very similar to the "Cyclids" group. When the search was repeated using a bit less rigorous approach (thresholds multiplied by 1.05) all members of this association have bound together with association 495. When more rigorous approach was applied this association survived, however with less in number.

Association 177. With D_V function and thresholds given in Table 1, this group consists of 49 meteoroids and 198 minor planets. Using D_{SH} function, this group was detected in form of two branches: association 796 and association 1612, see Table 6. 16 members of the association 796 and 11 of the association 1612 are members of the association 177. Also, inside our associations 177, we have noticed several members of associations A4, A8, A9, A10 and A13 identified by Drummond (2000). Using more rigorous approach, associations 796 and 1612 have disappeared, the association 177 survived with less number of members, given in Table 6. The names of 63 asteroids the members of the reduced association 177 are given in Table 7.

Associations 43. When D_V function and thresholds given in Table 1 were applied this association formed a huge group already mentioned in section 4.2.2. When reduced approach was applied, the α Capricorniids has separated from this group, but still the group which remains is difficult for interpretation: 53 meteoroids and 429 asteroids has been detected in this group. With D_{SH}, we found 5 meteoroids and 17 asteroids only, all of them inside the huge group detected with D_V, see Table 6. Using more restrictive approach — D_V and

Table 8. The names of minor planets associated in groups 495, 657. By the color box we depicted the names of the planetoids selected by Brasser & Wiegert (2008) as the small Earth approaches (SEA).

Association 495							
1991VG	1992JD	1999CG9	1999FA	1992JD	2000SG344	2000SZ162	2001FR85
2001GP2	2001VC2	2002AA29	2002PN	2003YN107	2004JN1		2005CN61
2005FJ	2005UG5	2005UV64	2006BJ55	2006BZ147	2006DQ14		2006JY26
2006QQ56	2006SY5	2006UB17	2007MF	2007UN12	2007WA	2007XB23	2008CD70
2008EA9	2008EL68	2008JL24	2008KT				
Association 657							
138947	1993HD	1996XB27	1997YM9	2000CE59	2001QC34	2001VE2	2003SM84
2004EO20	2004FM32	2005FG	2005LC	2005TF45	2006CK	2006HC	2006MB
2006UQ216	2007HL4	2007RX8	2007TF15	2008CM74	2008CP	2008CX118	2008GL2
2008HU4							

thresholds from Table 1 multiplied by a factor 0.8 — the huge group decreased considerably, we found only 4 meteoroids and 13 asteroid associated in this group. The names of the remaining 13 NEAs are listed in Table 7. Among them we did not find the names of the associations detected in Drummond (2000).

5. Conclusions

In this study we have made the most extensive (up to now) and very rigorous search for grouping amongst photographic meteoroids, comets and asteroids. Many well established results have been confirmed: connections Perseids — comet Swift-Tuttle, Leonids — comet Tempel-Tuttle, Orionids and η Aquariids — comet Halley, December Monocerotids — comet Mellish, Lyrids — comet Thatcher, and Geninids — minor planet Phaethon. Also, using the method applied in this study we have found the asteroid 2003EH1 as the possible parent of Quadrantids stream.

No parent bodies were found for κ Cygnids and Northern and Southern δ Aquariids streams.

In case of Taurids, we found a complex group of 14 possible parent bodies listed in Table 5, six of them was already mentioned by several investigators.

The α Capricornids were also identified in this search, we found three possible parent bodies for this stream. We confirmed the already known connection with comet 169P/NEAT, but we added two additional hypothesis, the minor planets: 2002 NW and 2004 BA75.

Ten associations were found mainly consisted of minor planets, see Table 6. The reality of common origin of the members of these groups is an open question. However remarkably similarity of the orbits in e.g. association 694, allows to consider a common origin of this group. The results in this part of our study have a preliminary status.

Finally we have detected two groups of object moving on the orbits very similar to the Earth trajectory. Following an earlier discoveries we called this group “Cyclids” - associations 495 and 657. The dynamical studies of some of these objects (Brasser & Wiegert , 2008) pointed out that one can mostly rule out spacecraft or lunar ejecta as the origin of them, and thus, their most likely source is low-eccentricity Apollo and Amor asteroids.

Acknowledgements. TJJ work was supported by MNiSW Project N N203 302335. Some part of calculations was done at Poznań Super-computing and Networking Centre.

References

Asher, D.J., Clube, S.V.M., Steel, D.I. 1993, MNRAS, 264, 93
Babadzhanov P.B.. 2001, A&A 373, 329
Brasser R., Wiegert P. 2008, MNRAS, 386, 2031
Brown, P., Weryk, R.J., Wong, D.K., Jones, J. 2008, Icarus, 195, 317
Brown, P., Wong, D.K., Weryk, R.J., Wiegert P. 2010, Icarus, 207, 66
Drummond J.D. 1981, ICARUS 45, 545
Drummond J.D. 1991, ICARUS 89, 14

Drummond, J. D. 2000, *Icarus*, 146, 453
Gartrell G., Elford W.G. 1975, Aust.J.Phys, 28, 591
Galle, J.G. 1867, Astr. Nachr., 69, 33
Galligan D.P. 2001, MNRAS, 327, 623
Galligan D.P., Baggaley W.J. 2002a, IAU Coll. 181, Green S.F., Williams I.P., McDonnell J.A.M. and McBride N. (eds.), Oxford, Pergamon, 2002, 42
Galligan D.P., Baggaley W.J. 2002b, AU Coll. 181, Green S.F., Williams I.P., McDonnell J.A.M. and McBride N. (eds.), Oxford, Pergamon, 2002, 48
Galligan D.P. 2003, MNRAS, 340, 899
Hoffmeister, C. 1937, *Die Meteore*, Leipzig
Hoffmeister, C. 1948, *Meteorströme*, Verlag Johann Ambrosius Barth, Leipzig
IAU MDC, 2007: `http://www.astro.amu.edu.pl/~jopek/MDC2007/`
Jenniskens P. 2008a, Icarus 194, 13
Jenniskens P. 2008b, EM&P, 102, 505
Jenniskens P., Vaubaillon J. 2010, AJ139, 1822
Jewitt D., Weaver H., Agarwal J., Mutchler Max., Drahus M. 2010, Nature, 467, 817
Jopek T.J. 1986, In Ph.D. dissertation, A.M. University, Poznań, (in polish)
Jopek, T.J. 1993a, Icarus, 106, 603
Jopek T.J. 1993b, in Proc. of the IAU Symp., J. Stǒhl, I.W. Williams (eds.), Smolenice, Slovakia, July 1992, p. 269
Jopek, T.J., Froeschlé, Cl. 1997, A&A, 320, 631
Jopek T.J., Valsecchi G.B., Froeschlé Cl. 1999a, Mont. Not. R. Astron. Soc., 304, 751
Jopek, J.T., Valsecchi, B.G., Froeschle, Cl. 1999b, *Meteoroids 1998*, W.J. Baggaley, V. Porubcan (eds.), p. 307
Jopek T. J., Valsecchi, G. B. and Froeschlé Cl. 2003, MNRAS, 344, 665
Jopek T. J., Rudawska R. Bartczak P. 2008, EM&P, 102, 73
Jopek T. J., Koten, P. and Pecina P. 2010, MNRAS, 404, 867
Kasuga T., Balam D.D., Wiegert P.A. 2010, AJ140, 1806
Kholshevnikov, K.V., Vassiliev, N.N. 2004, 371, CMDA, 119
Kostolancky E. 1998, Contr. of the Astron. Observ. Skalnate Pleso, 28, 22
Lindblad B.A. 1971a, Smith.Cont.Aph. 12, 1
Lindblad B.A. 1971b, Smith.Cont.Aph. 12, 14
Lindblad B.A. 1974. IAU 22nd Colloquium, Asteroids, Comets, Meteoric Matter, Cristescu C., Klepczynski W.J., Milet B. (eds.), 269
Lindblad B.A. 1992, in Proc. ACM 1991, p. 363
Lindblad B.A. 1994, ASP Conference Series, 63,62
Lindblad, B.A., Neslušan, L., Porubčan, V., Svoreň, J. 2003, EM&P, 93, 249
Lovell, C.P. 1954, *Meteor astronomy*, Oxford, At the Clarendon Press
Marsden B.G., Williams G.V. 2003, Catalog of cometary orbits 2003, 15th edition
NEO Dynamic Site, 2008: http://newton.dm.unipi.it/neodys
Neslušan, L., Welch, P. G. 2001, Meteoroids 2001 Conference, ESA SP-495, 113
Nilsson C.S. 1964, Aust. J. Phys., 17, 205
Olivier, C.P. 1925, *Meteors*, Willams & Wilkins Company, ch. 4
Olsson-Steel, D. 1988, Icarus, 75, 64-96.
Öpik, E.J. 1976, *Interplanetary Encounters*, Elsevier, New York
Pape, C.F. 1861, Astr. Nachr., 55, 206
Porubčan V., Štohl J., Vaña R. 1991, in Asteroids, Comets Meteors, 473
Porubčan V., Gavajdova M. 1994, Planetary and Space Science, 42,151
Porubčan V., Kornoš L., Williams I.P. 2006, Contr. Astr. Obs. Skalnaté Pleso, 36, 103
Pravec P., et al. 2010, Nature, 466, 1085
Rudawska R. 2010, In Ph.D. dissertation, A.M. University, Poznań, (in polish)
Sekanina Z. 1970a, Icarus 13, 459
Sekanina Z. 1970b, Icarus 13, 475
Sekanina Z. 1973, Icarus 18, 253
Sekanina Z. 1976, Icarus 27, 265
Southworth R.B., Hawkins G.S. 1963, Smith. Cont. Aph. 7, 261
Steel, D.I., Asher, D.J., Clube, S.V.M. 1991, MNRAS, 251, 632
Štohl J., Porubčan V. 1991, Interplanetary Matter, (Ceplecha Z., Pecina P. eds.), vol. 2, p. 24
Štohl J., Porubčan V. 1991, Dynamics of the Small Bodies of the Solar System, (Ziólkowski K. ed.), p. 43

Svoreň, J., Neslušan, L., Porubčan, V. (2002), PSS, 48, 933
Terentjeva, A.K. 1967, Smit. Cont. Aph., vol. 11, 109
Valsecchi, G. B., Jopek T. J. and Cl. Froeschlé. 1999, MNRAS, 304, 743
Vereš, P., Klačka J., Kómar L., Tóth J. 2008, EM&P, 102, 47
Weiss, E. 1867, Astr. Nachr., 68, 382
Welch, P.G. 2001, MNRAS, 328, 101
Whipple, F. L. 1938, Harvard Reprint 152, 499
Whipple, F. L. 1951, ApJ, 113, 464
Whipple, F. L. 1954, AJ, 59, 201