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A stream search among 502 TV meteor orbits. An objective approach

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Abstract. In the first part of the paper a short review of the computer meteor stream searching techniques is given. Different fractions of the stream component obtained amongst radio, photographic and TV data are partially due to the use of different methods applied in the stream search. A new objective approach is proposed in order to obtain the threshold value D_c of the orbital similarity corresponding to the probability of chance occurrence of the stream. The 502 Canadian TV data has been used to test this approach. It appears, that the values of D_c given by Southworth & Hawkins (1963), and Lindblad (1971b) formulae are too high to warrant sufficient reliability of the identified streams. Indeed using these formulae the result is that the probability to obtain by chance at least one stream of 4-5 members goes from 21% to 68%. The effect of the three different distance functions used to measure the orbital similarity (Southworth & Hawkins (1963), Drummond (1979, 1981), and Jopek 1993) has been investigated. For all functions taking the same 95% reliability level, the number of streams detected is considerably less than in the case of the traditional approach (Jopek 1993a). However, results are different using different distances. Finally, we give the list of the orbits of eight streams identified at the reliability level W_M = 95% using the Jopek distance.

Key words: meteors

1. Introduction

The computer stream-detection technique has been introduced by Southworth & Hawkins (1963). The authors devised all the components necessary for a computer cluster analysis:

- a distance function – the function D_{SH} of the orbital similarity named by them the D-criterion,
- a rule for calculating the threshold value D_c for orbital similarity,
- a stream searching algorithm which, together with the D-criterion and D_c, can be considered as a definition of a meteor stream.

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Tables 6 and 7 are only available in electronic form at the CDS via ftp 130.79.128.5 or http://cdsweb.u-strasbg.fr

Three distance functions have been proposed (see Appendix for the mathematical formulation): the Southworth & Hawkins (1963) distance D_{SH}, its modification D_D made by Drummond (1979,1981) and an alternative hybrid D_H given by Jopek (1993b).

Southworth & Hawkins (1963) proposed two definitions of a meteor stream given below. In both cases a meteor stream is defined as a significant concentration of orbits in orbital elements space.

Definition 1 *Let $O_k = \{q, e, \omega, \Omega, i\}_k$, $k = 1, ..., N$ be a set of N meteor orbits. Let O_m be a mean orbit of the stream, known a priori, let D_{km} be the distance between O_k and O_m. A meteor stream S is defined as a subset of orbits for which:*

$$S = \left\{ O_k, k = 1, \ldots, n : \underset{k \leq n}{\forall} D_{km} < D_c \right\}$$

Definition 2 *Let O_k stands for the same as above and D_{kl} be the distance between O_k and O_l, then a meteor stream S is defined as the subset of orbits:*

$$S = \{O_k, k = 1, \ldots, n :$$

$$\underset{k \leq n}{\forall} \left[\underset{k_1 \leq n, k_1 \neq k}{\exists} D_{k_1 k} < D_c \right.$$

$$\wedge \underset{k_2 \leq n, k_2 \neq k_1}{\exists} \left(D_{k_2 k} < D_c\right) \vee \left(D_{k_2 k_1} < D_c\right)$$

$$\ldots$$

$$\wedge \underset{k_n \leq n, k_n \neq k_{n-1}}{\exists} \left(D_{k_n k} < D_c\right) \vee \left(D_{k_n k_1} < D_c\right) \vee \ldots$$

$$\left. \ldots \vee \left(D_{k_n k_{n-1}} < D_c\right) \right] \}$$

Definition 1 is clear – a meteor stream consists of the orbits concentrated around the adopted mean one. In a five dimensional phase space defined by the orbital elements, a meteor stream is a set of points inside a hyper-sphere of radius D_c and a centre at the mean orbit. This definition can be applied to find members of known streams, that may exist amongst a given orbital sample. Definition 2 is more complicated and general than definition 1. In practice it is realized as a cluster analysis algorithm based on a single neighbour linking technique and it has the advantage of not demanding any a priori orbital information regarding the meteor stream, thus it can be applied for new streams. The algorithm can be illustrated by the formation of the following structures. First we have to find all associated groups of points, and so we calculate the mutual distance D_{kl} for every pair of points O_k and O_l, and connect them by a section if $D_{kl} < D_c$. As the calculations proceed the groups of conected points enlarge, and within each group, each point is associated with at least a single neigbhour. When the calculations are completed for the entire meteor sample, there will appear several structures of connected points (compact groups or chains of points) each of which may be considered as a stream.

Nilsson (1964) defined a meteor stream using four orbital elements: the reciprocal of the semimajor axis, the eccentricity, the inclination and the true anomaly (or equivalently, due to the Earth crossing condition the argument of perihelion). The longitude of the ascending node was ignored as the observations he analysed, were made over a short period (5-10 days) each month.

Definition 3 *Let $O_k = \{a, e, \omega, i\}_k, k = 1, ..., N$ be a set of N meteor orbits. The association between two orbits O_k and O_l observed in the same month requires that all the following conditions are satisfied:*

$$\begin{aligned}
&\left|\frac{1}{a_k} - \frac{1}{a_l}\right| \leq 0.15 \quad \left[\frac{1}{AU}\right], \\
&|e_k - e_l| \leq 0.07, \qquad\qquad (1) \\
&|i_k - i_l| \leq 7^\circ, \\
&|\omega_k - \omega_l| \leq 7^\circ,
\end{aligned}$$

and, a meteor stream is a group of orbits whose elements lie within a total range, not exceeding twice the values given in (1).

In terms of this definition and a four dimensional phase space, a meteor stream consists of points inside a four dimensional paralellelepiped. It can be applied for searching new streams.

Sekanina (1970a, 1976) defined a meteor stream by applying the D_{SH} distance function but instead of the requirements that stream members satisfied Definition 1, he proposed an iterative procedure to determine the mean orbit of a stream defined as follows.

Definition 4 *Let O_k and D_{kl} have the same meaning as in Definition 2. A meteor stream S is defined as the outcome of the following iterative process:*

1. *select an initial mean stream orbit;*
2. *in the sense of Definition 1, find all orbits for each $D_{kl} < D_c$;*
3. *using these orbits calculate a new mean orbit; the contribution of each meteor is weighted proportionally to $(1 - D_{kl}/D_c)^h$, where the constant h equals 1 or 2;*
4. *repeat steps 2 and 3 with the new mean orbit until new orbital elements converge;*
5. *a meteor stream is a group of meteoroids which contributed to the final mean orbit.*

Definition 4 is similar to Definition 1 – one can consider a meteor stream as a set of points inside a hyper-sphere of constant radiuns D_c, however, as iteration advances, the centre of the sphere moves from one place to the other converging to the final mean orbit. Sekanina's definition is convienient for finding all members of known streams. Searching for unknown streams becomes difficult as the sample size grows, since in principle the orbit of any single meteor could be taken as the initial orbit.

In Definitions 1, 2 and 4, two orbits are associated if a value of D does not exceed a certain threshold D_c. Using a four-dimensional point distribution as a model of the distribution of meteor orbits and a list of meteor streams obtained earlier, Southworth & Hawkins concluded that D_c should vary inversely with the fourth root of the sample size N. They proposed the following formula:

$$D_c = 0.2\left(\frac{360}{N}\right)^{1/4}. \qquad (2)$$

This formula has been modified by Lindblad (1971b), who proposed:

$$D_c = 0.8\,(N)^{-1/4}. \qquad (3)$$

In the very first computer search Southworth & Hawkins (1963) applied Definition 1 and 2 to a sample of 359 meteor orbits. Lindblad, using the distance function D_{SH}, Definition 2 and a threshold D_c given by formula (3), identified streams among 865 precise photographic orbits (Lindblad 1971a), and among 2401 photographic orbits reduced graphically (Lindblad 1971b). He extended his studies to include 1827 precisely reduced photographic orbits (Lindblad 1971c). Results of these searches were compared with those obtained by the same method among 325 small camera photographic orbits (Lindblad 1991). The D_{SH} distance and Definition 2 were used by Jopek (1986) in a computer search amongst 1608 precise photographic meteor orbits. 531 double station TV meteor orbits have been searched by Jopek (1993a). In this study Definition 2 and the hybrid distance function D_H are applied. The first radio meteor streams were detected by Nilsson (1964) who studied orbital associations within a set of 2101 meteors observed at Adelaide during 1961. A second Southern hemisphere radio meteor survey was made by Gartrell & Elford (1975). In this study 1667 orbits were analysed using the Nilsson stream Definition 3, and Definition 2 of Southworth & Hawkins. The same

Table 1. General results of the several previous computerized stream searches. Mg - limiting magnitude of the observed meteors, N - number of the orbits, D - distance function, D_c - orbital similarity threshold level, N_t - total number of the identified streams, S_t - total fraction of the stream component. The value of N_t denoted by an asterisk was derived from Lindblad (1974).

Author	Mg	N	D	D_c	N_t	$S_t[\%]$
Southworth,Hawkins (1963)	phot. +3	359	D_{SH}	0.2	34	53
Nilsson (1964)	radio +6	2101	–	–	71	22
Lindblad (1971a)	phot.+3	865	D_{SH}	0.15	78	45
Lindblad (1971b)	phot.+3	2401	D_{SH}	0.115	198	43
Lindblad (1971c)	phot.+3	1827	D_{SH}	0.13	164*	55
Sekanina (1973)	radio +13	19303	D_{SH}	0.2	83	7.5
Gartrell,Elford (1975)	radio +8	1667	D_{SH}	0.1,0.2	196	40
Sekanina (1976)	radio +13	19698	D_{SH}	0.06-0.1, 0.25	275	16
Jopek (1986)	phot. +3	1608	D_{SH}	0.12-0.2	88	58
Lindblad (1991)	phot. –	325	D_{SH}	0.20	14	83
Jopek (1993a)	TV +8.5	531	D_H	0.2	22	32

streams were detected although in some cases there were minor variations in subgrouping. Sekanina (1970a,1970b,1973,1976) studied streams amongst Northern hemisphere radio meteors. Sekanina (1970a,b,c) applying Definition 4 conducted a limited search; in a sample of 19303 orbits he identified members of known streams, as well as assembling around initial orbits obtained by some three dimensional scheme. Sekanina (1976) used another approach, this time the author searched for meteor streams in two steps. First, the initial orbits were found using Southworth & Hawkins Definition 2. The whole sample of 19678 orbits was divided into ten subsets and each were searched for streams. In the next step the Sekanina iterative algorithm (Definiton 4) was applied. All the results quoted above are summarized in Table 1.

There have been other searches through the IAU meteor data at Lund, to increase the number of meteors belonging to various known streams. Wu & Wiliams (1992) found 118 orbits which they suspected belonged to the Quadrantid meteor stream from about 69000 meteor orbits. Wiliams & Wu (1993) conducted a search in order to obtain the most complete sample of the Geminid meteors. A total 610 orbits, 100 photographic and 510 radar, were selected as the Geminid stream memebers. Also Harris & Hughes (1995) made a search through the IAU photographic meteor data for possible Perseids meteors. The end-product of this study was the selection of 245 photographic Perseids. All the authors used used the iterative search method given by Sekanina (1970a) and the distance function D_D of Drummond (1979, 1981). Following Drummond's suggestion (Drummond 1981), they took the threshold $D_c = 0.105$ to indicate the orbital similarity.

2. The objectives of the present paper

In Table 1 we observe striking differences between the percentage contribution of the stream component in the photographic, TV and radio meteor data. Several reasons for the differences can be indicated:

- the radio meteor observations are dominated by very small particles producing meteors up to +13 radar magnitude. Such particles are strongly affected by different non-gravitational factors and are dispersed faster into the sporadic background.
- the scatter of the measured orbital elements of stream meteors results from the actual differences between the orbits as well as from the measurement errors. The precision of photographic orbits is such that the real scatter in the values of the elements greatly exceeds the random deviations due to measurement errors. On the other hand the limited precision of radio data can cause relatively large scatter of orbital elements due to the errors in measurement alone.
- last but not least, the discrepances are caused by the use of different methods of identification of streams: different cluster analysis algorithms, different rules for the choice of the threshold level. Moreover, the authors rather subjectively decided on inclusion of streams of two, three or more members should be included into the final results.

Southworth & Hawkins (1963) and Nilsson (1964) investigated the reliability of their results by searching for streams in equivalent sets of artificial data that were constructed by shuffling and re-assigning appropriate orbital elements. Nilsson claims that the number of spurious streams found in this way is an upper limit to that in the true sample, as the artificial sample is based upon the orbital elements of a set of data which already contains a significant proportion of streams. Due to limitation of the computing power at that time it was rather problematic to accomplish an extensive reliability test of the detected streams. Fortunately, nowadays there is no problem in including in every stream searching process a more detailed significance test.

Our purpose is to improve the meteor stream searching procedure so as to make it objective and to demonstrate its efficiency by taking three distance functions and the double station TV meteor data published by Hawkes et al. (1984), Jones & Sarma (1985), Sarma & Jones (1985). These data sets have already been used by Jopek (1993a) to detect meteor streams among 531 orbits, using a traditional approach, namely: D_H distance function, Definition 2 of a meteor stream and the threshold $D_c = 0.2$ was adopted, so as to give the best fit with the photographic meteors streams. A few tens of formal groups were

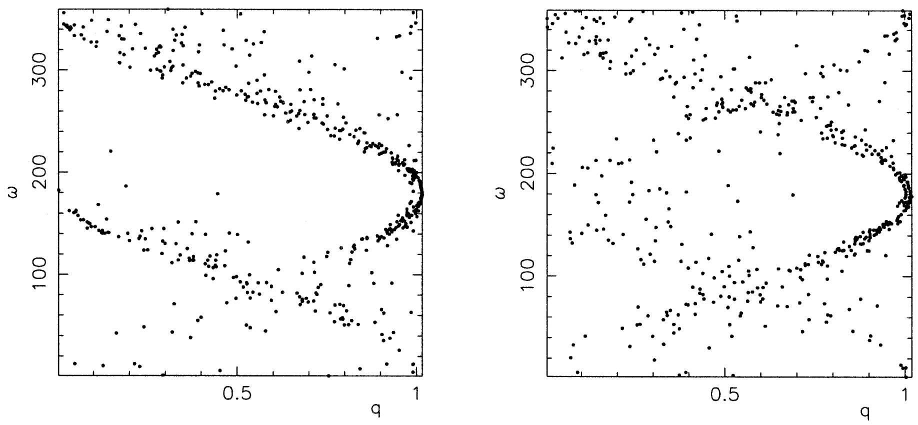

Fig. 1. Appearance of the Earth collision condition selection effect in the ω, q distributions. One can see distinct similarity between the two diagrams corresponding to the observed sample (on the left) and the artificial one (on the right) obtained by our quasi-random meteor orbit generator.

detected and 22 were accepted as meteor streams. The stream component represented 32% of the orbital sample. However, no significance tests had been performed. In the present studies a more objective procedure is developed and applied to the same orbital sample. Taking from the source catalogues: the apparition time, geocentric coordinates of the radiant point and the pre-atmospheric geocentric velocity, all orbits have been recalculated. Next, we rejected all orbits having $e > 1.5$, this reduced the sample size to 502 items.

3. Components of meteor streams searching method

As was mentioned earlier, in order to develop the stream searching method, one has to specify: the distance function, the threshold value of the orbital similarity and the cluster analysis algorithm.

3.1. Choice ot the distance function

As a consequence of our earlier studies (Jopek 1993b) we have decided to compare three distance functions: D_{SH}, D_D and D_H given by formulae (A1),(A2) and (A3) respectively (see Appendix).

D_{SH} and D_H are quite similar and differ only by a weighting factor in the second term of both functions. The Drummond D_D function is not equivalent to D_{SH} and D_H, what arises from the conceptual differences between the fourth terms of the functions. For the case of the function D_D, its fourth term is a measure of the angle made by Laplace vectors of the two compared orbits, and in the functions D_{SH} and D_H, the fourth term equals to the difference in the longitudes of perihelion measured from the point of intersection of the orbits. (For details see Jopek 1993b).

3.2. The cluster analysis algorithm

The cluster analysis algorithm was chosen after comparison of our own implementation of Definition 2 with the hierarchical clustering method (the nearest neighbour variant), the software was kindly given to us by A. Cellino (see Zappalá et al. 1990, 1994). The two methods turned to give identical results. In further studies we have used our own routine.

In the present comparison we have not included the Nilsson method. as there is a serious reason which prevents us from using this method. When the distance functions are considered, the threshold choice is a one dimensional problem while Nilsson's method deals with a five-dimensional one.

Jopek (1989) found certain convergence problems using the Sekanina method, that is sometimes slow and spurious convergences (already stated in Sekanina 1970a), and sometimes even a lack of convergence. Therefore the Sekanina approach was not included for comparisons.

3.3. Objective choice of the orbital similarity threshold D_c

The threshold D_c is the crucial parameter of any cluster analysis. Up to now D_c was estimated by formula (2) or (3). However these formulae are only approximations; formula (2) was established on the basis of a small photographic orbital sample, and formula (3) is only a simplification of the previous one. Moreover, due to different precision and statistical distributions of meteor data, application of the formulae (2), (3) to any type of data is not justified (see Jopek 1995). We need the value of D_c to be related to a reliability test of the identified streams. In order to obtain numerical solutions, about two hundred artificial samples have been generated and analysed by the stream searching software. Thus, we estimated the probability of a occurrence of a stream of M members as a chance grouping. Such an approach requires a suitable random orbits generator. The observed distribution of meteor orbits is very far from uniform one and in addition it is not the outcome of a pure stochastic process. Several observation selection effects should be taken into account, in particular the Earth collision condition (see an example in Fig. 2). At the time a meteor is observed:

$$r = \frac{q(1+e)}{1 \pm e\cos\omega}, \tag{4}$$

where $r \cong 1[AU]$, is the heliocentric distance of the meteoroid, and the sign at the $e\cos\omega$ is positive if the geocentric ecliptic

Table 2. Results of the cluster analysis among 502 artificial orbits. D_c – threshold level, S_t – total percentage of the associated orbits, S_M the number of groups of M=2,3 ... members.

D_c	S_t[%]	S_2	S_3	S_4	S_5	S_6	S_7	S_8	...
...	...	...	...	...	...	...	...	...	...
0.08	5.6	11	2	0	0	0	0	0	...
0.09	7.8	15	3	0	0	0	0	0	...
0.10	10.2	18	5	0	0	0	0	0	...
0.11	11.4	19	5	1	0	0	0	0	...
0.12	14.1	23	5	1	0	1	0	0	...
0.13	17.7	25	4	2	2	0	0	1	...
...	...	...	...	...	...	...	...	...	...

Table 3. The threshold levels D_{cS} for 502 TV meteor orbits. The given values refer to the general sporadic bias $S_t = 1 - 15\%$ and the distance function D_{SH}, D_H, and D_D, respectively.

	D_{cS}		
	(D_{SH})	(D_H)	(D_D)
S_t = 1%	0.091 ± 0.016	0.088 ± 0.016	0.043 ± 0.008
S_t = 5%	0.138 ± 0.011	0.136 ± 0.012	0.067 ± 0.006
S_t = 10%	0.171 ± 0.010	0.169 ± 0.011	0.083 ± 0.006
S_t = 15%	0.196 ± 0.010	0.194 ± 0.010	0.096 ± 0.005

latitude of the meteor radiant $\beta_G < 0$.

Accordingly, quasi-random meteor orbits have been obtained by the following procedure:

1. obtain the observed distributions of: orbital elements, the heliocentric distance and the ecliptic latitude of the meteor radiant,
2. using observed distributions, generate independently: r, β_G, e, ω, Ω, i,
3. having r, β_G, e, ω calculate q.

This algorithm provides Earth crossing orbits with marginal distributions of orbital elements similar to the observed ones (as example see Fig. 2). Moreover, the quasi-random orbits are not associated in the genetic sense. About two hundred samples of 502 artificial orbits have been generated. Statistical consistence between each of these samples and the observed one has been confirmed by using the chi-square test (Knuth 1971). Each sample was analysed separately by the same stream searching software, Table 2 depicts an example of the outcome of a single analysis. Results taken from about two hundred such tables enabled us to assess the parameters of interest. We paid attention to the following outcome:

– S_t - the total fraction of the orbits identified as group members for a given D_c,
– S_M - the number of groups of M members detected for a given D_c.

The value of S_t obtained for the artificial orbits gives the expected fraction of sporadic interlopers (sporadic bias) among the streams detected in the real sample. Fig. 2 shows the changes of S_t against the threshold D_c. The D_{SH} and D_H functions appear to be equivalent concerning variations of S_t.

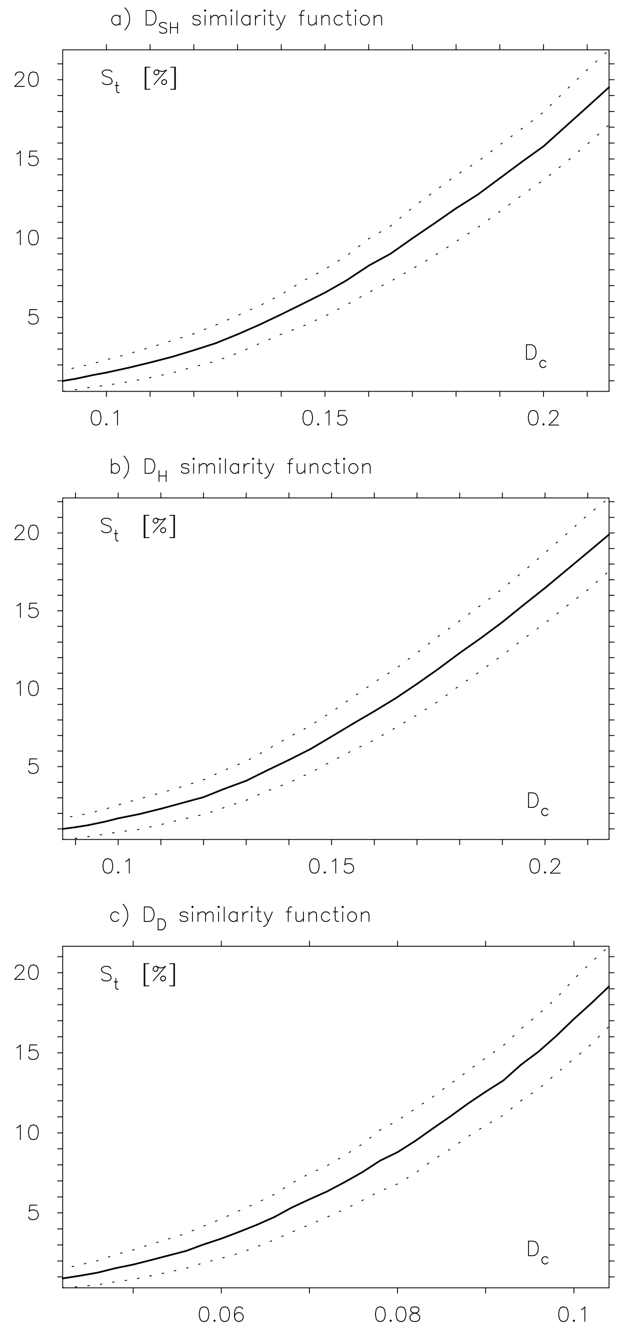

Fig. 2. Mean percentage of the associated orbits S_t versus threshold D_c (the solid curve). The dotted curves are one sigma deviations from the corresponding values of S_t. Plots a), b), c) correspond, respectively, to D_{SH}, D_H and D_D orbital distance function. Because the D_{SH} and D_H average 2 times the value of D_D, the scale for the horizontal axis of the plot c) has been increased by the same factor.

The curves in Fig. 2 have an important meaning. They allow an assessment of the orbital similarity threshold corresponding to the chosen value of S_t (see Table 3). Inversely, they can be used to find the values of S_t corresponding to the threshold given for example by formulae (2) or (3). Inserting into both formulae N=502 yields D_c = 0.184 or D_c = 0.169, respectively. For the D_{SH} distance function, the corresponding values of the spo-

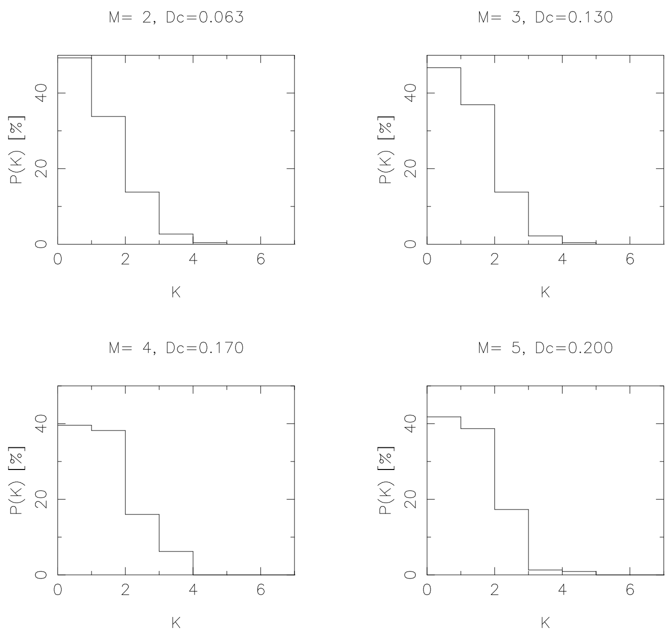

Fig. 3. Probabilities of chance occurrence of K group of M members, by given D_c. (D_H distance function).

radic bias are S_t = 13 $\pm$ 2.2% and S_t = 10 $\pm$ 2%, respectively. In Table 3 there are more examples of this relation.

To obtain more detailed information about the infiltration of the sporadic interlopers we have used all S_M values taken from about two hundred tables of the structure given in Table 2. Our purpose was to find the smallest threshold D_{cW} for which the probability Pr($K = 1, M = const$) of occurrence of a $K = 1$ group of M members equals, say 5%. The quantity:

$$W_M = [100 - \mathrm{Pr}(K = 1, M = const)]_{D_{cW}} \quad [\%] \qquad (5)$$

is the reliability level of the meteor stream of M members identified by the threshold D_{cW}. For different values of M and D_c we computed the frequences F_K, $K = 0, 1, 2, ...$ of the occurrence of the K group of M members. Fig. 3 shows some examples of such frequencies (probabilities). Using the least square method, the polynomial relation between the frequencies F_1 and the corresponding thresholds D_c was then established in order to find the values of D_{cW} for a given $P(K = 1, M = const)$. The plots of such a relation are shown in Fig. 4. We see that for higher values of M the relation is problematic, presumably due to the small size of the orbital sample used.
The final calculated values of the smallest thresholds D_{cW} for several reliability levels W_M are shown in Table 4. The method described above was also applied to find the probabilities of chance occurrence of a stream of M members identified by the orbital similarity thresholds calculated by formulae (2) and (3). We found that for 502 TV orbits, using these thresholds, the probabilities of a chance occurrence of at least one stream of 4 members are 68% and 54%, respectively. When the number of members is increased to 5, these probabilities drop to 38% and 21%.

Table 5. List of meteor streams and number of members detected by the search at W_M = 95% using three distance functions D_{SH}, D_H, D_D. The last column shows the number of members selected at D_c = 0.2 in Jopek (1993a).

	Number of orbits			
Name	D_{SH}	D_H	D_D	D_c = 0.2
S. Taurids	13	13	10	15
S. Taurids-Arietids	12	10	0	14
α Capricornids	11	12	10	23
κ Cygnids	6	10	24	24
δ Aquarids	12	9	0	12
Perseids	6	6	14	17
Cyclids	5	5	3	-
ϵ Pegasids	2	2	2	-
Aquilids	0	0	4	-

4. The results and the list of TV meteor streams

Several runs to search for meteor streams among 502 TV orbits have been made. We accept all streams detected with the thresholds D_{cW} for which $W_M \geq$ 95%. Starting from M=2 members, all the pairs with $D_{ik} < D_{cW}$ have been found. In the next run (with the new threshold D_{cW} and $W_M \geq$ 95%) all the stream of M = 3 members have been found, which possibly, have included some sub-streams already found as 2 member streams, and so on. We have imposed one more condition. Namely, the highest threshold applied should not cross the value corresponding to 10% of the general sporadic bias, given in Table 3. Hence, the last run for the D_{SH} function for example, was made with $D_{cW} = 0.171$ for which all groups of $M \geq 8$ were accepted as sufficiently reliable.

For the functions D_{SH} and D_H eight streams have been found corresponding to 13.3% of the orbital population. In the case of D_D function, seven streams were detected making 13.5% of 502 orbits. Thus, the general outcomes are quite similar. However, detailed findings reveal some important differences. Table 5 shows a list of names of all identified streams and the number of members. Table 6 and 7 gives the full data on the eight streams identified by our method and the D_H orbital similarity function. Additionally, they contain the mean values and standard deviations for the orbital parameters of all streams except Cyclids and ϵ Pegasids. Reliability of the Cyclids has only statistical meaning, they do not origin from the same parent body.

In Tables 6 and 7 instead of the argument of perihelion ω, we show the longitude of perihelion $\pi = \Omega + \omega$. It is more useful to describe the orientation of the line of apside of the meteor orbit. To form mean orbital elements of such streams, we have assumed all orbits to be the southern type (with negative ecliptic latitude of the radiant point) by adding 180^o to the node, and interpreting them as having negative inclinations. Tables 6 and 7 are followed by a series of figures illustrating the orbits of all members of the streams.

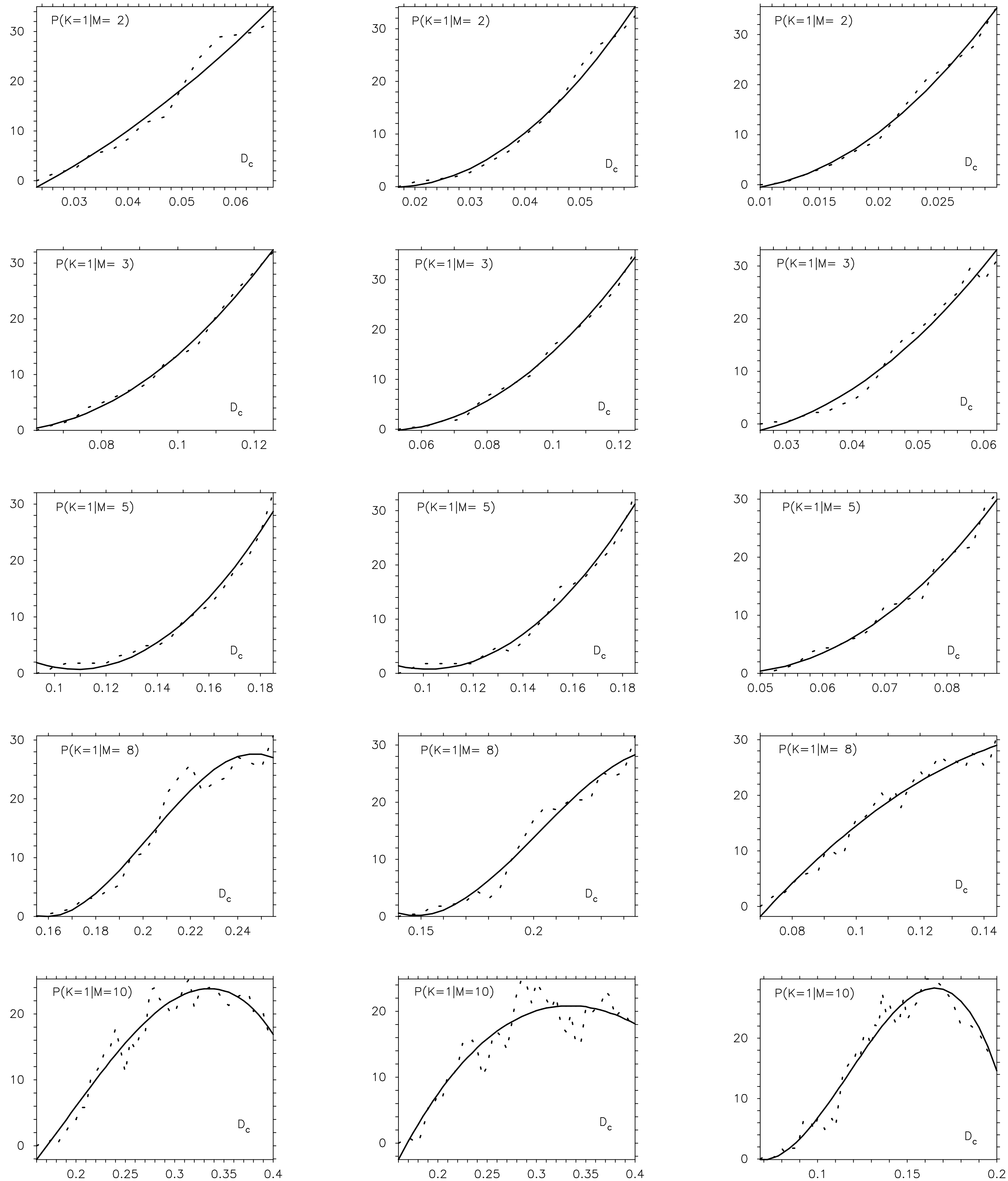

Fig. 4. Examples of the relation between the probability of a chance occurrence of a single group of M members and the threshold D_c. From the left the plots correspond to the D_{SH}, D_H and D_D distance functions. The smoothed curves are the least squares approximations of the values of $P(K = 1, M = const)$ obtained by numerical simulation.

Table 4. Results of the choice of the orbital similarity threshold for 502 TV meteor orbits. The values of D_{cW} for each stream membership M correspond to the reliability levels W_M equal 95 − 99%.

	D_{cW}								
	W_M = 99%			W_M = 98%			W_M = 95%		
M	(D_{SH})	(D_H)	(D_D)	(D_{SH})	(D_H)	(D_D)	(D_{SH})	(D_H)	(D_D)
2	0.025	0.025	0.013	0.029	0.028	0.014	0.035	0.034	0.017
3	0.067	0.063	0.033	0.072	0.068	0.036	0.082	0.078	0.040
4	0.105	0.100	0.047	0.110	0.105	0.050	0.121	0.114	0.054
5	0.102	0.108	0.054	0.116	0.118	0.056	0.137	0.132	0.062
6	0.132	0.130	0.061	0.143	0.137	0.064	0.157	0.149	0.071
7	0.150	0.144	0.072	0.157	0.150	0.075	0.170	0.163	0.080
8	0.168	0.158	0.073	0.174	0.164	0.075	0.185	0.177	0.083
9	0.172	0.164	0.080	0.180	0.170	0.083	0.195	0.183	0.090
10	0.183	0.174	0.077	0.190	0.180	0.083	0.203	0.195	0.097

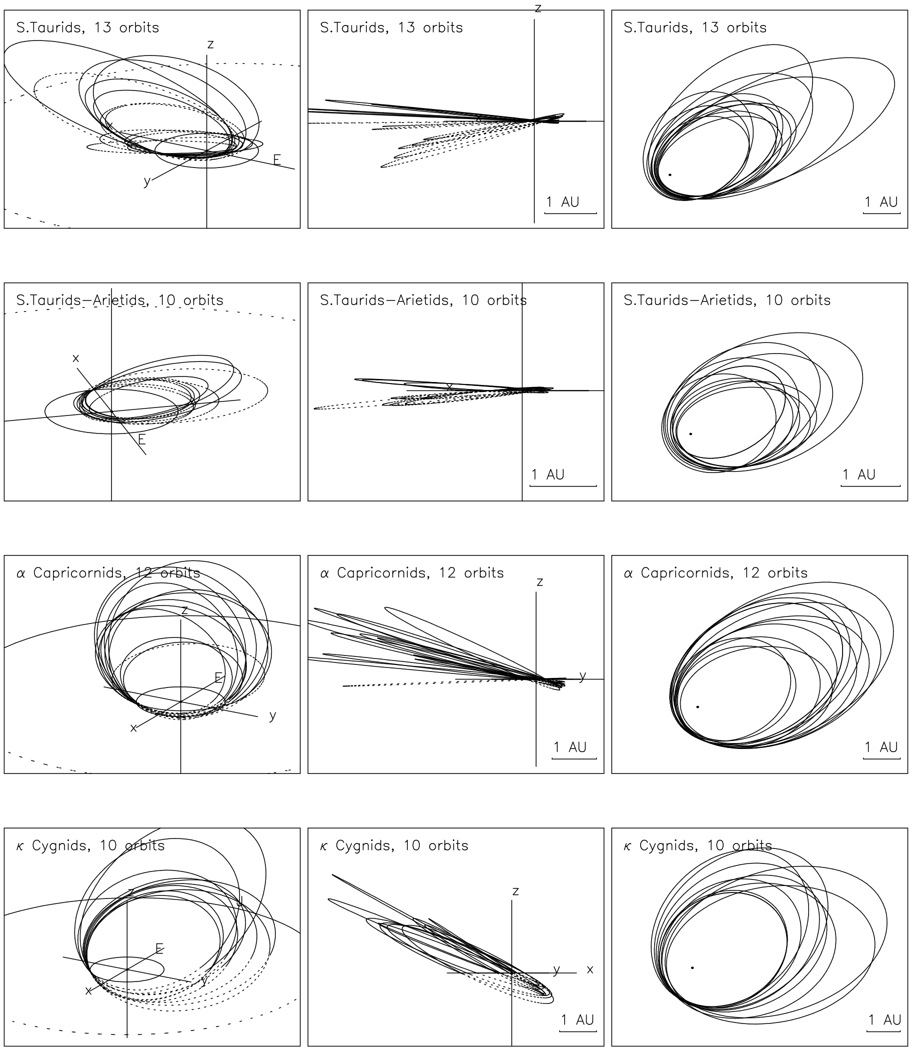

Fig. 5. The meteor orbits identified as stream members among 502 TV data. For each stream three projections are given. The second one is made on the plane perpendicular to the Earth orbit. The third one is a projection on the orbital plane of first member of the stream listed in Table 6 or 7. The parts of the orbits below the ecliptic are plotted by the dotted line. The Earth and Jupiter orbits are denoted by the letter E and J.

5. Discussion

All the streams but one (the ϵ Pegasids – two almost identical orbits) show some differences, indicating that the distance functions are not equivalent. This is particularly true for the D_D function. At the reliability level 95% the Southern Taurids and δ Aquarids have not been detected by the Drummond function. The same was observed for the Aquilids shower and the D_{SH} and D_H functions. All these groups were detected when the reliability level was decreased to 90% or 85%.

In the case of Cyclids, κ Cygnids and Persids we see significant difference in the number of the orbits identified as stream members. The small number of Cyclids and the high number of

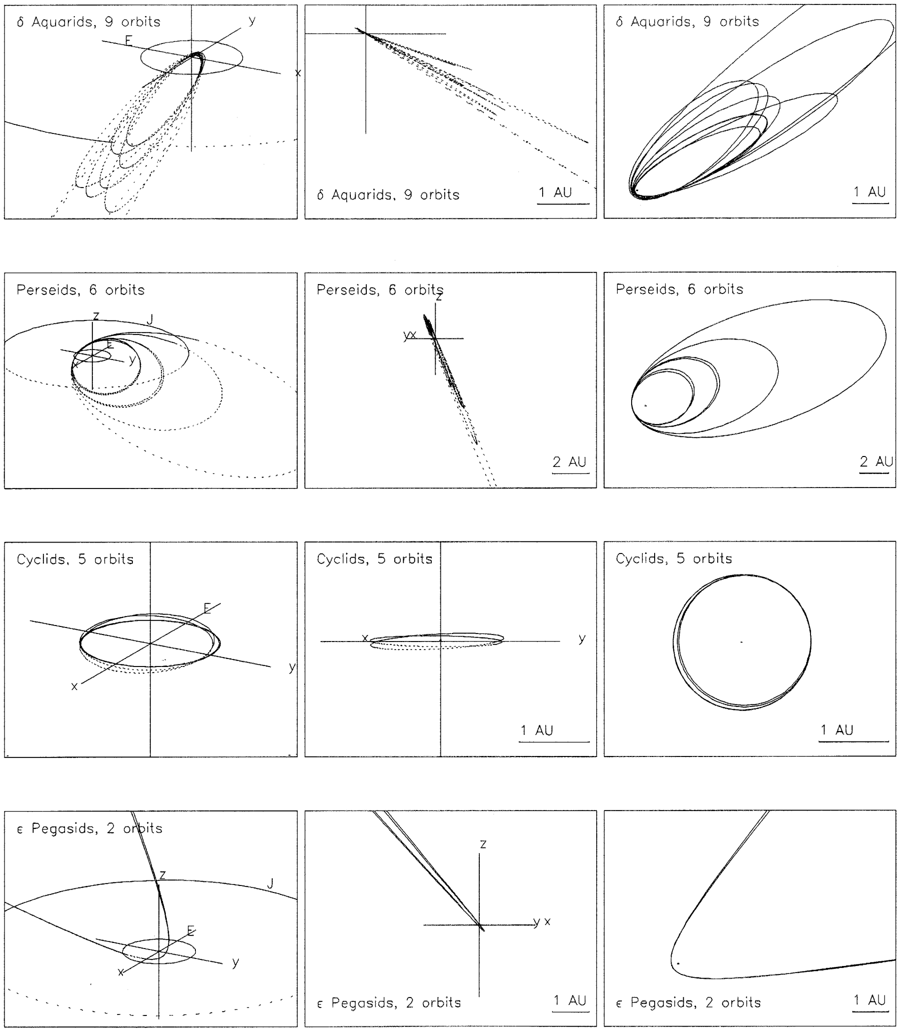

Fig. 6. Illustrations of the meteor orbits - continuation.

Perseids given by Drummond function are a consequence of the weighting factor $1/(e_k+e_l)$ in the first term of D_D (see Eq. (A2). When small values of eccentricities occur (Cyclids) the first term of D_D function is very high, even when the value of $(e_k - e_l)$ is rather small. For high eccentricities (Perseids) the first term of D_D function is always smaller than for D_{SH} and D_H functions. Therefore in Table 5 we observe a smaller number of Cyclids and higher number of Perseids identified with the Drummond function. The same cause contributes to a higher number of κ Cygnids detected using the D_D function. In this case we observe an additional influence of the weighting factor $1/(q_k + q_l)$ in the second term of D_D and D_H functions. Typical value of the perihelion distance of κ Cygnids meteor orbit equals 0.9 AU. The opposite influence of the factor $1/(q_k + q_l)$ is observed in Table 5 for δ Aquarids ($q \sim 0.1AU$), and Southern Taurids ($q \sim 0.35AU$). In the case of the Aquilids stream the reasons for the discrepancies are more complicated. Detailed tracking of the searching software has shown that for this stream the highest contribution of the D_{SH} and D_H function was given by the third and fourth terms, whereas the contributions in the D_D function for all terms were on the same level.

The present study has shown that only 7 from 22 groups identified by the traditional approach (Jopek 1993a) are sufficiently reliable, namely: S. Taurids, S. Taurids-Arietids (N. Taurids in Jopek 1993a), Capricornids, κ Cygnids (Herculids in Jopek 1993a), δ Aquarids (α Pegasids in Jopek 1993a), Perseids and Cyclids. However, many of these streams have significantly fewer members than in the previous search (see Table 5). As a result of a decrease in the number of streams as well in the number of stream members, only 13.3% of the sample still belonged to the stream component. In the search made by Jopek (1993a) 32% of the orbits belonged to the streams. These results are in better agreement with those obtained earlier by Sekanina and Nilsson using the radio meteor data (see Table 1). In comparison with Jopek (1993a), the streams not recovered in the present study include two branches of Orionids (9 members) and several minor groups (5-6 members): γ Serpentids, ω Piscids, β Triangulids, ϑ Aquarids and π Cepheids. All these groups have the probability of chance occurrence higher then 5%.
The dates covered by the TV observations (fall between July 06 and November 4) explaining the absence of the other streams: Geminids, Quadrantids, Virginids and Leonids showers among the 502 TV data.

Table 8. Mean orbital elements of the meteor streams given by: C-73 – Cook (1973), GE-75 – Gartrell & Elford (1975), HH-95 – Harris & Hughes (1995), J-86 – Jopek (1986), JF – Jopek & Froéschle present paper, L-71 – Lindblad (1970b), L-91 – Lindblad (1991), N-64 Nilsson (1964), PS-87 – Porubčan & Štohl (1987), SP-91 – Štohl & Porubčan (1991), S-70 – Sekanina (1970b), S-76 – Sekanina (1976), SH-63 – Southworth & Hawkins (1963). In the last column the distance D_H between JF mean orbit and the others are given.

Author	e	q AU	$\Omega+\omega$ deg	Ω deg	i deg	D_H
			S. Taurids			
N-64	0.50	155	56	4.2	0.76	0.137
S-70	0.385	163.7	47.9	1.4	0.770	0.201
L-71	0.330	147.5	28.7	3.3	0.828	0.111
C-73	0.375	153.2	40.2	5.2	0.806	0.074
GE-75	0.30	153	24	7.1	0.82	0.174
J-86	0.328	147.6	28.1	5.7	0.821	0.119
PS-87	0.370	150.2	36.7	5.4	0.819	0.064
SP-91	0.366	149.7	35.4	5.5	0.814	0.066
L-91	0.370	150.1	37.8	3.1	0.821	0.055
L-91	0.343	154.9	39.9	6.5	0.852	0.141
JF	0.404	149.3	39.2	3.4	0.791	0.000
			S. Taurids-Arietids			
SH-63	0.322	149.3	39.2	3.4	0.819	0.318
S-73	0.273	134.7	7.8	1.4	0.841	0.193
JF	0.335	126.8	359.9	2.9	0.720	0.000
			α Capricornids			
SH-63	0.663	41.0	142.2	8.0	0.773	0.156
L-71	0.592	33.3	125.4	7.1	0.760	0.096
S-73	0.630	54	146.8	0.9	0.659	0.347
C-73	0.59	36	127	7	0.77	0.110
J-86	0.608	34.1	127.4	7.2	0.740	0.096
L-91	0.576	37.1	126.9	7.3	0.758	0.113
L-91	0.727	28.2	317.4	2.8	0.729	0.287
JF	0.602	32.3	125.1	12.5	0.751	0.000
			κ Cygnids			
S-73	0.927	355.6	152.5	42.9	0.621	0.340
J-86	0.987	341.1	145.3	34.6	0.716	0.250
L-91	0.985	347.5	147.7	38.2	0.769	0.289
L-91	0.955	347.6	139.7	29.1	0.717	0.129
JF	0.902	352.2	130.5	27.9	0.647	0.000
			δ Aquarids			
SH-63	0.066	98.1	304.6	28.9	0.974	0.238
L-71	0.074	98.7	307.1	28.4	0.972	0.188
C-73	0.069	97.8	305.0	27.2	0.976	0.216
S-70	0.083	99.2	307.3	29.9	0.955	0.148
S-76	0.069	101.1	305.7	28.2	0.958	0.237
J-86	0.093	100.3	311.4	26.0	0.961	0.123
JF	0.104	93.9	307.2	27.8	0.960	0.000
			Perseids			
L-71	0.934	286.6	138.7	113.2	0.920	0.240
C-73	0.953	290.5	139.0	113.8	0.965	0.310
S-76	0.960	292.2	139.7	110.2	0.881	0.251
J-86	0.948	288.5	138.0	112.9	0.973	0.311
L-91	0.947	288.5	138.3	113.1	0.964	0.299
L-91	0.940	287.8	139.2	113.0	0.877	0.208
HH-95	0.949	289.6	138.8	113.1	0.969	0.307
JF	0.910	277.6	138.9	112.1	0.721	0.000

Tables 6 and 7 list six streams already recognized earlier. In Table 8 we have collected the mean orbital elements obtained in the present search and those given by other investigators. In the last column we put the distances D_H between our mean orbits and other cited orbits. We have a good agreement between these orbits for the Southern Taurids, but poor one for the Perseids. Our Perseids mean orbit differs significantly from all the others. Generally, in Table 7 the members of the TV Perseids have smaller eccentricities and perihelion distances when compared with the values given in Table 8.

It is difficult to explain why for each stream we have such differences amongst the mean orbits. Undoubtedly, any mean orbit given in Table 8 is biased by several observation selection effects: the period covered by observation, the observational techniques and sensitivity of the equipement, the observation site. They are also biased by the distance function, the algorithm and the similarity threshold used in the stream search. It is a further argument for improving the stream searching procedure and make it more objective.

6. Conclusions

We have developed an objective procedure for meteor streams identification. Of key importance in such a procedure is a choice of the threshold of the orbital similarity. Our approach gives the threshold corresponding to the probability of chance occurrence of a group of M members in the given orbital sample. For testing, we have used 502 TV orbits and three existing measures of the orbital similarity. At the reliability level 95% we have found 7-8 meteor streams. Differences in the outcome obtained by three distance functions indicate that the problem of the orbital similarity is still opened, at least in case of the meteor data. In our opinion, the same is true when we consider the problem of the cluster analysis algorithm.

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Appendix A: Formulation of the orbital distance function

The problem is to define the function which measures the distance between pair of meteor orbits. In a five dimensional coordinate system based on the differences between the osculating orbital elements e, q, ω, Ω, i, three distance functions have been proposed:

– the Southworth and Hawkins (1963) distance D_{SH}, which for a pair of meteors kl, gives:

$$D_{SH}^2 = (e_k - e_l)^2 + (q_k - q_l)^2 + + \left(2\sin\frac{I_{kl}}{2}\right)^2 + \left(\frac{e_k + e_l}{2}\right)^2 \left(2\sin\frac{\pi_{kl}}{2}\right)^2, \quad \text{(A1)}$$

where I_{kl} is the angle between the orbital planes and π_{kl} is the difference between the longitudes of perihelia measured from the common node of the orbits:

$$\left[2\sin\frac{I_{kl}}{2}\right]^2 = \left[2\sin\frac{i_k - i_l}{2}\right]^2 + \sin i_k \sin i_l \left[2\sin\frac{\Omega_k - \Omega_l}{2}\right]^2 ,$$

$$\pi_{kl} = (\omega_k - \omega_l) + +2\arcsin\left[\cos\frac{i_k + i_l}{2}\cdot\sin\frac{\Omega_k - \Omega_l}{2}\cdot\sec\frac{I_{kl}}{2}\right] ,$$

where the sign of the arcsin should be opposite when $\mid \Omega_k - \Omega_l \mid > 180°$.

– Drummond (1979,1981) proposed another function which utilizes a particular set of weights to render each of the terms into natural units and linear over a similar range:

$$D_D^2 = \left(\frac{e_k - e_l}{e_k + e_l}\right)^2 + \left(\frac{q_k - q_l}{q_k + q_l}\right)^2 + + \left(\frac{I_{kl}}{180^o}\right)^2 + \left(\frac{e_k + e_l}{2}\right)^2 \left(\frac{\theta_{kl}}{180^o}\right)^2 , \qquad \text{(A2)}$$

where θ_{kl} is the angle between the lines of apsides of the orbits:

$$\theta_{kl} = \arccos\left[\sin\beta_k \sin\beta_l + \cos\beta_k \cos\beta_l \cos(\lambda_k - \lambda_l)\right] ,$$

where λ, β are ecliptic coordinates of the perihelion point given by:

$$\lambda = \Omega + \arcsin(\cos i \tan\omega) \quad (add\ 180° \ if \ \ \cos\omega < 0),$$

$$\beta = \arcsin(\sin i \sin\omega).$$

– Jopek (1993b) has shown that the functions (A1) and (A2) are not equivalent. As a result of numerical analysis of the properties of D_{SH} and D_D, he proposed an alternative hybrid discriminant, namely:

$$D_H^2 = (e_k - e_l)^2 + \left(\frac{q_k - q_l}{q_k + q_l}\right)^2 + + \left(2\sin\frac{I_{kl}}{2}\right)^2 + \left(\frac{e_k + e_l}{2}\right)^2 \left(2\sin\frac{\pi_{kl}}{2}\right)^2 . \qquad \text{(A3)}$$

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