SMITHSONIAN CONTRIBUTIONS to ASTROPHYSICS

Number 12

Two Computerized Stream Searches Among Meteor Orbits: 1. Among 865 Precise Photographic Orbits; 2. Among 2401 Photographic Orbits

By Bertil-Anders Lindblad

Smithsonian Institution
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Bertil-Anders Lindblad

1. A Stream Search Among 865 Precise Photographic Meteor Orbits

Introduction

Meteors are generally divided into two classes —shower meteors and sporadic meteors. About a dozen major showers occur every year. These showers, or streams, are conspicuous in any list of visually observed or photographed meteors, and virtually all their members are readily identifiable. If the shower radiant is diffuse or the hourly rate is low, however, it is not easy to recognize a meteor stream.

The division into stream metors and sporadic meteors is, to a certain extent, arbitrary. The classifications hitherto used for stream identification are based primarily on geocentric quantities such as radiants, velocities, and dates of occurrence. When, in addition, detailed orbital information is available for individual meteors, the above methods of classification are supplemented or superseded by methods based on comparisons of sets of orbital elements. The use of the orbital elements has the advantage that these parameters are more fundamental, having regard to the initial formation of a stream.

Owing to inherent differences among the individual members of a meteor stream, the investigator who makes a stream search is faced with the difficult problem of rejecting suspected stream members when the orbital elements exhibit too large a deviation from some assumed mean set of orbital elements. The rejection level adopted as well as the assumed set of mean elements is necessarily somewhat subjective, being largely based on the investigator's *a priori* knowledge of the dispersion within the stream.

It is difficult to recognize members of a previously unknown stream or members of a stream not well represented in the sample under study. The problem of stream identification becomes increasingly difficult in large samples owing to the amount of labor involved and also to the possibility of spurious associations among different sets of orbital elements. The expected existence in the near future of very large collections of fairly precise meteor orbits determined by photographic and radio methods makes it necessary to introduce a quantitative criterion for stream membership as well as an automatic method of stream search suitable for computer analysis.

The D-criterion of stream membership

Southworth and Hawkins (1963) present a study they made of the statistics of meteor streams. The study is based on a quantitative measure of orbit similarity, which the authors call the *D*-criterion. Their method depends on the principle of intercomparison of two sets of orbital elements. Let *A* and *B* represent two individual meteors to be tested for orbit simi-

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larity. Let the orbital elements be represented by the five quantities q, e, i, Ω, and π, where, as usual, $q = a(1-e)$ is the perihelion distance, e the eccentricity, i the inclination, Ω the longitude of the ascending node, and $\pi = \omega + \Omega$ the longitude of perihelion, measured from the vernal equinox.

Let I_{AB} be the angle between the orbital planes and π_{AB} the difference between the longitudes of perihelion measured from the intersection of the orbital planes. Further, let the differences of angular orbital elements be measured by their chords, i.e., by twice the sine of half the angle. A quantitative measure of orbit similarity (or difference) is then given by the expression

$$[D(A,B)]^2 = (e_B - e_A)^2 + (q_B - q_A)^2 + \left(2\sin\frac{I_{AB}}{2}\right)^2 + \left[\frac{1}{2}(e_A + e_B)\ 2\sin\frac{\pi_{AB}}{2}\right]^2, \qquad (1)$$

where $\frac{1}{2}(e_A + e_B)$ is a weight function. The last two terms in equation (1) are related to the orbital elements as follows:

$$\left(2\sin\frac{I_{AB}}{2}\right)^2 = \left(2\sin\frac{i_B - i_A}{2}\right)^2 + \sin i_A \sin i_B \left(2\sin\frac{\Omega_B - \Omega_A}{2}\right)^2 \qquad (2)$$

and

$$\pi_{AB} = \omega_B - \omega_A + 2\ \mathrm{arc\ sin}\left(\cos\frac{i_A + i_B}{2}\sin\frac{\Omega_B - \Omega_A}{2}\sec\frac{I_{AB}}{2}\right). \qquad (3)$$

In the definition of D, the difference in perihelion distance is substituted for the semimajor axis a as a measure or orbit size, because the perihelion distance is well determined by observations and exhibits a small range of values. This is particularly important in the analysis of photographic meteor data, which often contain a high percentage of nearly parabolic orbits.

Having acquired a quantitative measure of orbit similarity, let us proceed to the definition of a meteor stream. A criterion of stream membership may be based on either of the following two definitions:

1. As previously, a stream may be defined by a comparison of the orbital elements of an individual member N with the corresponding elements of a mean orbit M. Let $D(M, N)$ have the same mathematical form as $D(A,B)$ of equation (1). A stream may then be defined as all those meteors N whose difference $D(M, N)$ from the mean orbit M is less than a certain prescribed amount $D_{\max}$.

2. A stream may be defined by serial association between the members. Two meteors A and B are said to be associated if $D(A, B)$ does not exceed a standard value D_s. A stream may then be defined as a group of meteors in which every member is associated with one or more of the other members.

ADOPTED METHOD OF STREAM SEARCHING.—Of the two definitions mentioned above, the latter has the advantage of not demanding any *a priori* knowledge of the orbit of a meteor stream and is therefore suitable for a computer search for streams. A computer program based on the concept of serial associations has been worked out by Southworth. The method of stream search consists essentially of labeling the meteors in a sample, in some order, and computing first the orbital difference $D(A, N)$ between a meteor A and all the other meteors in the sample, and second the orbital differences between meteor B and the other members, etc. As soon as a pair is detected by the condition $D<D_s$, where the standard value of D_s has been prescribed in advance, these two meteors are said to form a stream. Eventually more meteors will be included in the stream by the continued comparison process. When the computer has run through the entire process, there will appear several groups or chains of meteors, each of which may be considered a stream. The program then numbers the streams and computes a mean orbit M for each of these streams, the difference $D(M, N)$ between each stream member N and this mean orbit, the equatorial coordinates (α, δ) of the mean radiant, and the mean geocentric velocity of the stream.

A difficulty encountered in the study of large data samples is that the above method of serial association sometimes produces a long chain, or string, of meteors wherein consecutive meteors exhibit a high degree of orbit similarity, but where the first and last meteor in the chain exhibit very little resemblance to each other or to the stream mean. This case reveals its presence through the very large $D(M, N)$ values exhibited by most members of the "stream." If a mean $D(M, N)$ is computed for all members of the stream, its value will greatly exceed the prescribed value of D_s. To overcome this difficulty, the numerical value of D_s has to be adjusted to the size of the sample under study.

Present investigation

Southworth and Hawkins (1963) applied the D-criterion to a sample of 360 meteor orbits. The data represented a random sample of meteors photographed from two stations by the Harvard Super-Schmidt meteor cameras (Hawkins and Southworth, 1958). In the present paper, the study is extended to include 865 precise photographic two-station orbits of the Harvard Meteor Program. The purpose of the investigation was twofold: to study how the numerical value of D_s should be adjusted to fit a larger sample, and to present the streams detected by the new stream search together with a short discussion of their orbital properties.

The 865 meteors comprised 139 small-camera orbits published by Whipple (1954), 313 Super-Schmidt meteor orbits published by Hawkins and Southworth (1961), and 413 Super-Schmidt meteor orbits listed by Jacchia and Whipple (1961). Of the published small-camera orbits, 5 were excluded because of incomplete data. Of the 360 orbits in the random sample of Super-Schmidt meteors, 47 were excluded since they are already included in the 413 orbits listed by Jacchia and Whipple.

The orbital elements and other relevant data for each meteor were available on cards, together with the shower (or sporadic) classification proposed by the original investigator. A few meteors originally classified as sporadic have in subsequent papers been reclassified as shower meteors; these reclassifications are listed in various papers of the Harvard Meteor Program (Wright, Jacchia, and Whipple, 1957; Hawkins, Southworth, and Stienon, 1959; McCrosky and Posen, 1959) and were taken into account in this analysis.

Application of stream search to known streams.—Once a computer procedure for stream searching has been established, it remains to determine the rejection level, i.e., the numerical value of D_s that should be used in the search. Southworth and Hawkins adopted the rejection level $D_s=0.20$, because when $D(A, B)$ was computed for all possible pairs within each of the recognized meteor showers in their survey, the value of $D(A, B)$ never exceeded 0.20. They noted that the rejection level D_s would have to be decreased in a sample larger than that under study (360 meteors). The authors predicted that D_s should vary inversely as the fourth root of the sample size. Hence, $D_s=0.20\left(\frac{360}{865}\right)^{1/4}=0.161$ would be an appropriate value to use in the present study.

To avoid prejudicing our choice, we decided to run independent stream searches at several levels of D_s. The 865 sets of orbital elements were therefore tested for stream membership at the rejection levels $D_s=0.20$, 0.15, and 0.10. The results of these searches are given below.

The first stream search revealed that at the rejection level $D_s=0.20$ it was not possible to single out the previously known meteor streams of low inclination. To illustrate the difficulties encountered in the search, we mention that one meteor stream of low inclination extended from July to December and included the α Capricornids, the χ Orionids, the Andromedids, and the Northern and Southern Taurids. In a similar manner, the Virginid stream combined with a group of 88 sporadic meteors to form one vast, low-inclination meteor stream extending from February through June. These results clearly indicate that the value of the rejection level D_s had been set too high. Although no further use is made of the search at $D_s=0.20$, it may be mentioned that at this rejection level the stream search singled out all the previously known meteor showers of moderate and high inclination.

The results of the search at $D_s=0.15$ are presented in Table 1. The first column gives the arbitrary stream number assigned by the computer program to the shower, the second the

TABLE 1.—*Previously known streams detected by stream search at* $D_s = 0.15$

Stream no.	Name	Previous members	New members	Total no. in stream at D_s = 0.15	Previous members rejected by stream search	
					No.	Harvard serial no.
2	α Capricornids	18	2	20	-	
14	χ Orionids	3	7	10	-	
18 52	Andromedids	3 2	9 -	12 2	1 -	5332
23	Northern ι Aquarids	2	1	3	2	3419 8075
36	Virginids	3	-	3	3	0828 1934 10247
40	Southern Taurids Northern Taurids	30 19	5	54	4 1	2961 3886 5124 9416 2630
13 22 45	Southern ι Aquarids	2 1 2	- 1 -	2 2 2	3	3784 8098 8307
65	Northern δ Aquarids	5	1	6	-	
71	Southern δ Aquarids	11	-	11	-	
72	Geminids	50	-	50	1	9507
74	Draconids	2	-	2	1	4513
76	κ Cygnids	8	1	9	2	2643 4472
79	Quadrantids	14	-	14	2	6093 6105
80	Lyrids	5	-	5	2	1910 10531
82	Perseids	27	-	27	5	1089 2049 2801 4216 8348
84	σ Hydrids	4	1	5	1	2328
87	Leonids	5	-	5	2	1898 2179
88	Orionids	17	1	18	6	2691 4974 5063 5183 5210 5231
	Total	233	29	262	36	

name of the shower, and the third the number of shower meteors, according to conventional classification, that were retained by the stream search. The fourth column lists the number of new members detected by the search. The fifth column in the table gives the total number of members in a stream as defined by the computer program. The last two columns list previous shower members that were rejected in the computer search.

Table 1 lists 19 previously recognized meteor streams for which more than one meteor existed in the sample. Inspection of Table 1 reveals that, with one exception, the computer program successfully identified and singled out the known meteor streams. The Andromedid shower, however, was split up into two showers, and the very diffuse Southern ι-Aquarid stream into three separate components. The one apparent failure occurred in the vast Taurid meteor complex, where the stream search at $D_s=0.15$ did not separate the Northern and Southern Taurid meteor streams. The Taurid meteor shower is of very long duration, and it has presented considerable difficulties to conventional shower-identification techniques. The northern and southern branches of this stream may, however, be easily separated by inspection of the orbital elements, since the line of nodes is shifted by 180° (Whipple, 1938; Wright and Whipple, 1950).

The results of the stream search at $D_s=0.10$ are summarized in Table 2. Although most of the known showers were still identified by the search, as many as 71 previous members were rejected and only 3 new ones added. We therefore concluded that the rejection level $D_s=0.10$ imposed too stringent requirements on stream membership. Two streams disappeared entirely. The Taurid shower was split up into three components, while the North δ Aquarids and the κ Cygnids were split up into two separate showers. It is, however, interesting to note that at this level the Southern δ-Aquarid stream suffered no losses and that the Quadrantid and Geminid streams were essentially intact. This indicates a high degree of orbit similarity within these showers.

TABLE 2.—*Previously known streams detected by stream search at* $D_s = 0.10$

Substream no.	Name	Previous members	New members	Total no. in stream at $D_s = 0.10$	Previous members rejected by stream search
27	α Capricornids	9	-	9	9
9	χ Orionids	3	-	3	-
34	Andromedids	2	-	2	-
-	Northern ι Aquarids	-	-	-	4
-	Virginids	-	-	-	6
20 22	Southern Taurids	15 9	- -	15 9	11
17	Northern Taurids	18	1	19	1
8	Southern ι Aquarids	2	-	2	6
38 44	Northern δ Aquarids	2 3	- -	2 3	- -
41	Southern δ Aquarids	11	-	11	-
42	Geminids	50	-	50	1
45	Draconids	2	-	2	1
49 50	κ Cygnids	2 4	- -	2 4	4
51	Quadrantids	14	-	14	2
52	Lyrids	4	-	4	3
54	Perseids	25	-	25	7
56	σ Hydrids	3	1	4	2
59	Leonids	4	-	4	3
60	Orionids	16	1	17	7
	Total	198	3	201	71

DISCUSSION—The results of the above three tests clearly illustrate the rather arbitrary character of a computer stream search and stress the need for a more precise definition of a meteor stream.

The best *D*-value to use in the present search was estimated as follows. Consider a large data sample already studied for streams. The computer search will reject some previously recognized members and include some "new" members. Since the number of new and rejected members varies from stream to stream, the value of D_s chosen should be such that the total number of rejections approximately equals the total number of new members. This approach gives us the best agreement with the conventional method of stream classification.

Table 1 indicates that among the known photographic streams, the search program at $D_s = 0.15$ rejected 36 previous members and added 29 new ones. We hence consider $D_s = 0.15$ to be very nearly the optimum value of D_s for use in the present sample. A detailed inspection of the rejected meteors revealed that there are often good reasons, according to conventional classification methods, for a rejection. Of the 36 previous members that were rejected in our search, 17 were either hyperbolic meteors or were classified by the original investigators as very doubtful members. If these objects are excluded from the list of previously known shower members, we find a net loss of 19 previous members and a gain of 29 new members.

In view of the above considerations, $D_s = 0.15$ is adopted as the rejection level. This empirically determined value of D_s is in good agreement with the value (0.161) based on the inverse fourth-root relation referred to earlier.

Further results of stream search at $D_s = 0.15$

In addition to the 19 streams (21 computer streams) listed in Table 1, the computer search at $D_s = 0.15$ produced an additional 59 meteor streams. The most significant of these are listed in Tables 3, 4, and 5. The identification and discussion of these new streams are the subject of the rest of this report.

COMPARISON WITH STREAM SEARCH OF MCCROSKY AND POSEN.—The existence of numerous weak meteor showers in the Harvard photographic data has become evident through several investigations. A study of 2529 Super-Schmidt meteor trails obtained during the period from February 1952 through July 1954 has been made by McCrosky and Posen (1961). Of the meteors photographed during this period, 2181 were reduced by an approximate, graphical method to yield radiants, velocities, and orbits.

Table 3.—*Comparison with new streams detected by McCrosky and Posen*

Stream no.	Name	Previous members	New members	Total no. in stream at $D_s = 0.15$	Previous members rejected by stream search	
					No.	Harvard serial no.
42	α Virginids (May)	-	-	-	-	
48	μ Pegasids	1	3	4	-	
86	Coma Berenicieds	-	2	2	1	1918
90	ε Geminids	1	2	3	-	
		2	7	9	1	

Remarks

The α Virginids are included in our σ–Leonid stream (table 4).

The μ Pegasids are identical with our α Pegasids (table 4).

In the compilation of table 3, only meteors common to the survey of McCrosky and Posen and our survey have been used.

A stream search based on conventional methods revealed seven new photographic showers (McCrosky and Posen, 1959). Three of the minor showers found by McCrosky and Posen also appear as separate showers in our data (Table 3). Another stream listed by these authors, the α Virginid, is included in the σ-Leonid stream found by Southworth and Hawkins and discussed below. Hence, of the seven showers found by McCrosky and Posen, four also appear in our smaller data sample.

Very little information is available on the recurrent nature of these minor streams. In one case (μ Pegasids), all four members of the stream were observed on two consecutive nights in the same year. Hence, some caution should perhaps be exercised in considering these minor streams as regular, recurrent phenomena.

Comparison with stream search of Southworth and Hawkins.—Southworth and Hawkins (1963) list 24 previously unknown meteor streams. Since their entire sample of 360 meteors is included in our data, it is of interest to compare the results of the two surveys.

Of the 24 possible new streams found by Southworth and Hawkins, 16 appear as separate streams in our search. These streams are listed in Table 4, together with the shower names proposed by Southworth and Hawkins. It should be noted that changes in the membership of these streams are very frequent. In a few cases, these changes shift the position of the radiant by several degrees. It would therefore perhaps be appropriate to rename a few of these streams. In order to avoid confusion in the nomenclature, however, we have refrained from changing the original designations listed in Table 4.

Table 4 includes three showers that appear in the stream search of McCrosky and Posen, and are therefore listed in Table 3 as well: the ϵ-Geminid stream bears the same name in both lists, the μ Pegasids of McCrosky and Posen are associated with our α Pegasids, and their α Virginids are included in our σ Leonids.

The inclusion of additional data in a second stream search may result in new stream members being detected in either of the following two ways: (1) a meteor orbit not previously studied may be classified as a shower member, and (2) a meteor orbit previously studied and rejected may be accepted in the second search because of the inclusion of new members in the shower. It is interesting to note that the second method of acquisition at $D_s = 0.15$ has operated

TABLE 4.—*Possible new streams detected by Southworth and Hawkins and found in present search*

Stream no.	Name	Previous members	New members	Total no. in stream at $D_s = 0.15$	Previous members rejected by stream search	
					No.	Harvard serial no.
3	Cyclids	5	1	6	-	
15	ρ Geminids	4	2	6	-	
19	μ Ophiuchids	2	1	3	1	8294
20	χ Geminids	1	2	3	3	6069 6098 6102
21	ξ Orionids	3	-	3	-	
29	ψ Ursae Majorids	2	2	4	-	
32	θ Ophiuchids	5	1	6	-	
42	σ Leonids	10	17	27	17	4012 6376 6458 6460 6484 6784 6803 6826 6885 6929 6992 7033 7056 12690 12752 10168 10193
48	α Pegasids	3	1	4	6	4432 4627 4842 8828 8844 9208
54	ω Ursae Majorids	2	3	5	1	7661
60	θ Herculids	1	1	2	2	8510 8699
66	τ Herculids	1	7*	8	1	7920
67	φ Bootids	2	-	2	1	12462
75	γ Bootids	2	1	3	-	
77	μ Draconids (June)	3	-	3	3	3346 7790 12592
90	ε Geminids	3	-	3	-	
	Total	49	39	88	35	

*Of the new members, one is from the smaller sample used by Southworth and Hawkins.

in the case of only one meteor shower, the τ Herculid, where it added one new member to the stream.

Southworth and Hawkins estimated that about half their newly found streams were spurious associations. It is convenient to divide the 24 new streams listed in Table 2 of their study (1963, pp. 268-272) into two groups according to the number of meteors in each stream. Of their new streams with 4 members or more, all 7 are verified by the present survey. In their shower list there are 7 streams with 3 members and 10 streams with 2 members. Of these minor streams, 6 of the former and 3 of the latter were detected in the present survey as well. Thus, approximately half their minor streams do not appear in the new search. Hence, with admittedly some simplification of the argument, we regard these streams as unverified. The disappearance of these minor streams is nearly always the result of a reclassification of the individual members as sporadic meteors.

The largest stream found by Southworth and Hawkins, and in the present study, is the σ-Leonid stream. In our data the activity of this shower extends from 18 March to 14 June and the stream consists of 27 members, of which 21 show a value of $D(M, N)$ larger than 0.15, i.e., larger than the adopted value of D_s. The mean value of $D(M, N)$ is 0.275. Inspection of Tables 4 and 6 reveals that the new stream search has drastically altered the membership list of this shower. It has also shifted the radiant by more than 20°, placing it in the constellation of Virgo instead of Leo. In view of these facts, we agree with Southworth and Hawkins that it is necessary to consider this shower a composite one. The correct interpretation of this stream must await further stream search in a much larger sample of precise orbits.

The next largest stream appearing in Table 4 is the τ Herculid, with 8 members. Its activity extends from 1 to 24 June and there is no pronounced date of maximum activity. Only 3 members show a value of $D(M, N)$ larger than 0.15, while the mean value of $D(M, N)$ is 0.128. The degree of orbit similarity within this stream resembles that found in such well-recognized showers as the Northern δ Aquarids and κ Cygnids.

NEW STREAMS FOUND IN PRESENT SEARCH.—

Summing up, the present study revealed 19 previously recognized meteor showers detected by conventional stream-identification techniques (Table 1), as well as 17 new minor showers discovered by McCrosky and Posen and by Southworth and Hawkins (Tables 3 and 4).

In addition, our search produced 42 new minor photographic "showers" each with from 2 to 7 members. Of these new streams, however, 37 have only 2 or 3 members each. In accordance with our previous findings, we now reject new streams with only 2 or 3 members on the belief that there is at least a 50-percent probability that they are spurious groupings in the data. Accordingly, we list in Table 5 as new photographic showers discovered by our search only those streams that have 4 or more members.

The new photographic streams found by us have been compared with various lists of meteor radiants published by visual observers. The λ Virginids are identical with the α Virginids of McIntosh (1935), while the ε Piscids appear to be related to the Piscid shower listed by Denning (1899) and Hoffmeister (1948). The θ Librids are identical with χ Scorpiids listed by McIntosh. The α-Virginid shower is a very prominent one in the radiant list of McIntosh (1935). It is interesting to note that several of our rejected two- or three-member streams have radiants that appear to be related to the

TABLE 5.—*Possible new streams detected by present search*

Stream no.	Name	Duration of stream	Solar longitude (1960)	No. of meteors	α_R	δ_R	V_G (km/sec)
10	κ Aquarids	18 Sept-12 Oct	175°-198°	4	341	- 3	19
16	λ Virginids	23 March-22 April	2 - 31	7	208	-14	32
17	θ Librids	23 May-7 June	61 - 76	4	238	-14	21
25	ε Piscids	2-12 Oct	188 -198	6	15	7	26
38	θ Cetids	27 Sept-12 Nov	183 -229	4	21	- 5	18

TABLE 6.—*Orbital elements of new photographic streams (equinox 1950.0)*

Stream no.	Name	Duration of stream	a	e	i	ω	Ω	π	α_R	δ_R	Harvard serial no.
3	Cyclids	10 Apr. -19 Oct.	1.01	0.087	1°9	83°0	52°1	135°1	61°	28°	4084 4952 7199 7326 12440
10	κ Aquarids	18 Sept. -12 Oct.	2.94	0.705	2.1	229.2	185.9	55.1	341	- 3	1514 4432 4624 4679
15	ρ Geminids	15-27 Jan.	2.66	0.710	3.5	243.4	301.4	184.8	110	29	0815 1988 6179 6245 6286 12193
16	λ Virginids	23 March-22 Apr.	2.32	0.861	2.8	119.4	196.8	316.2	208	-14	1937 3210 7073 7114 7333 10384 10439
17	θ Librids	23 May-7 June	2.63	0.713	3.3	249.1	70.5	319.6	238	-14	2863 7744 7788 12342
25	ε Piscids	2-12 Oct.	2.19	0.749	0.7	274.0	194.8	108.8	15	7	4728 4774 8800 8888 8974 9030
29	ψ Ursae Majorids	27 Feb. -21 Apr.	1.84	0.489	8.0	212.1	6.5	218.6	162	43	1920 6927 7179 10173
32	θ Ophiuchids	21 May-16 June	2.67	0.839	4.4	108.7	257.0	5.7	265	-27	3327 7726 7808 7871 7895 7899
38	θ Cetids	27 Sept. -12 Nov.	1.67	0.528	5.5	68.2	27.7	95.9	21	- 5	4659 4996 5047 9323
42	σ Leonids	18 March-14 June	2.56	0.683	3.1	239.7	31.8	271.5	195	1	1068 3246 3303 4111 6915 6971 7040 7056 7067 7135 7158 7184 7218 7240 7303 7324 7372 7388 7480 7494 7514 7520 7664 7734 7750 11825 11856
48	α Pegasids	11-12 Nov.	3.29	0.697	7.5	199.0	229.6	68.6	344	22	5370 5373 5375 5396
54	ω Ursae Majorids	21 May-5 June	2.93	0.653	16.7	170.5	66.3	236.8	174	67	3307 3312 3344 7745 7767
66	τ Herculids	1-24 June	2.90	0.660	20.7	203.6	80.8	284.4	236	41	2024 3346 4103 4125 7820 7882 12399 12711

α-Virginid radiant. The ϵ-Piscid stream is described by Denning as a very well-defined shower chiefly active in September and October.

ORBITAL ELEMENTS OF NEW STREAMS.—The mean orbital elements of all new photographic meteor showers with four or more members are summarized in Table 6. The table includes revised orbital elements of the eight showers detected by Southworth and Hawkins and verified by the present search, as well as the five additional showers detected by us.

For a meteor stream of small inclination, a large dispersion in i will result in meteors being observed simultaneously at both ascending and descending nodes. The stream members thus fall into two groups, the line of nodes differing by 180°. In the computation of the mean orbital elements for such a stream (Table 6), negative inclinations are introduced for one group, and Ω and ω are changed by 180°.

NUMBER OF METEORS IN STREAMS.—Inspection of Tables 1, 3, 4, and 5 shows that a total of 378 meteors in 41 showers were classified by us as stream meteors. Of an additional 82 meteors in 37 minor streams with only 2 or 3 members, it is estimated that about half may be real stream meteors. It is hence concluded that very nearly 45 percent of the meteor orbits could definitely be classed as streams, while a further 5 percent could probably be classed as members of minor streams. Thus at the rejection level $D_s = 0.15$, very nearly half the meteor population is composed of streams.

Relation between D(M,N) and orbital energy

After a meteor particle has been ejected from a parent comet, a number of perturbing forces act on it. These forces, both gravitational and nongravitational, will over a period of time produce substantial changes in the initial orbit. The cometary debris is thus dispersed into a series of orbits that exhibit a smaller or larger degree of similarity. This group of orbits we call a meteor stream, and the degree of similarity or dispersion is measured by the D-criterion.

During stream dispersion, the orbital energy of the various individual stream members will be changed. The orbital energy of an elliptical orbit is given by the quantity—$1/a$, where a is the semimajor axis. As a convenient measure of the scatter of orbital energy within a meteor stream, we now introduce the standard deviation of $1/a$ computed for all orbits belonging to the stream. This quantity may be used as an index of stream dispersion without making any assumptions as to the nature of the dispersing forces.

The standard deviation of $1/a$ was computed for all streams detected by the search at $D_s = 0.15$. In Figure 1A we have plotted $\sigma\ (1/a)$ against mean $D(M, N)$ for the 10 major showers with more than 9 members in our sample (Table 1). The corresponding quantities are plotted in Figure 1B for all streams with 4 or more members (Tables 1, 3, 4, and 5). As a fiducial point, the corresponding quantities for the Draconid shower are also included in the diagrams. A high correlation between the two measures of orbital scatter is evident. Since the D-criterion does not directly include the semimajor axis, this correlation is very encouraging. The evidence produced in the present investigation thus confirms that the D-criterion is a very useful measure of the amount of perturbation that will transform one orbit into another.

Velocity-elongation diagram

The mean geocentric velocity and the mean apparent elongation of the radiant from the earth's apex were computed for all streams detected in our search. Datum points for the previously known photographic showers listed in Tables 1 and 3 are plotted in the velocity-elongation diagram (Figure 2). The continuous curve in the diagram represents the theoretical relation between geocentric velocity and elongation assuming parabolic velocity at the earth's perihelion. Inspection of Figure 2 will show that comparatively few datum points appear in the lower right-hand part of the diagram. These points are all fairly near the parabolic curve. They represent meteor streams that are moving in retrograde orbits and whose members thus make head-on collisions with the earth's atmosphere.

The majority of meteor streams in the diagram cluster along a curve, which branches off

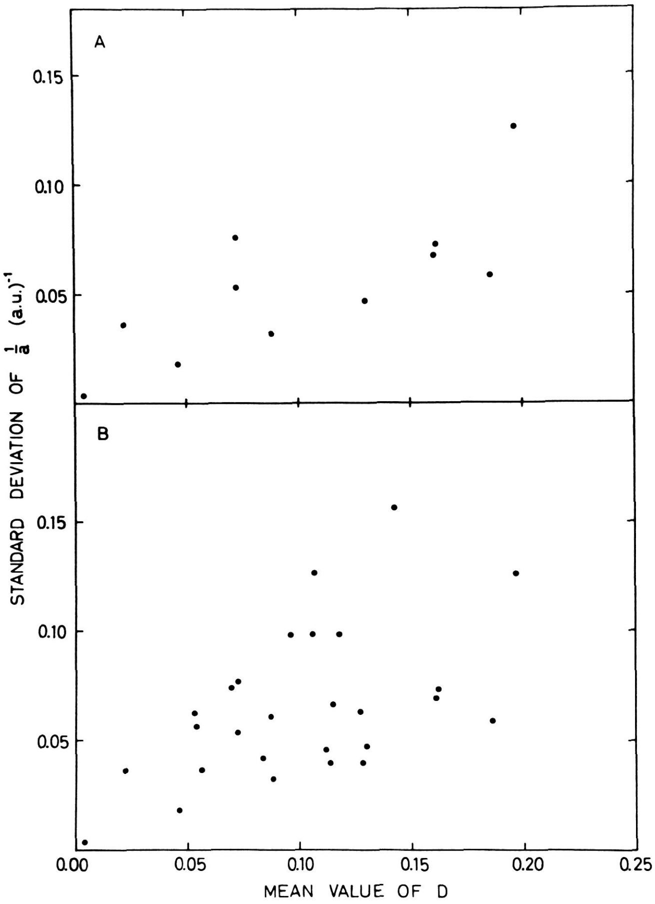


Figure 1.—Scatter of orbital energy vs mean *D(M,N)*: A, major photographic meteor streams; B, all photographic streams with four or more members.

Figure 2.—Velocity-elongation diagram for previously known photographic streams.

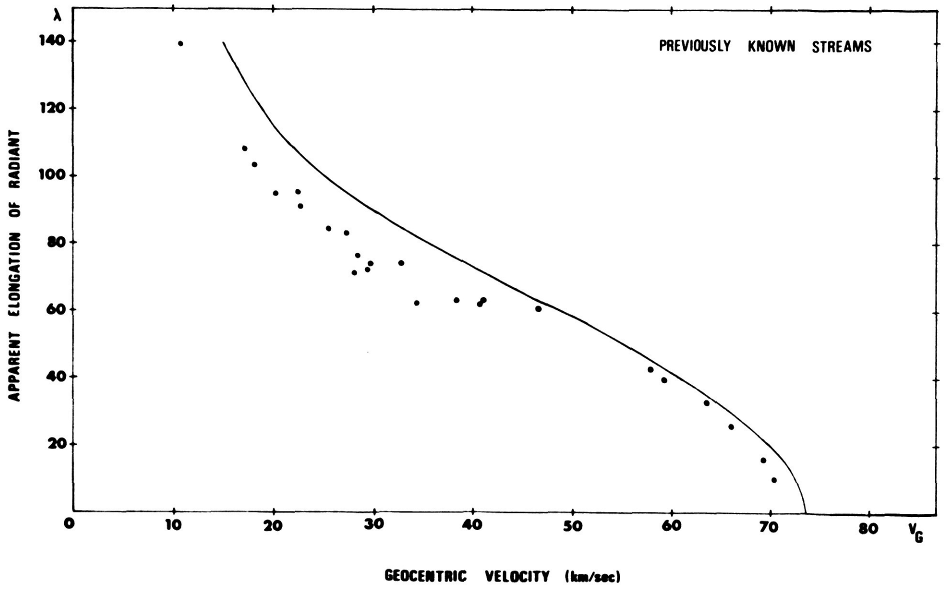


FIGURE 3.—Velocity-elongation diagram for new photographic streams.

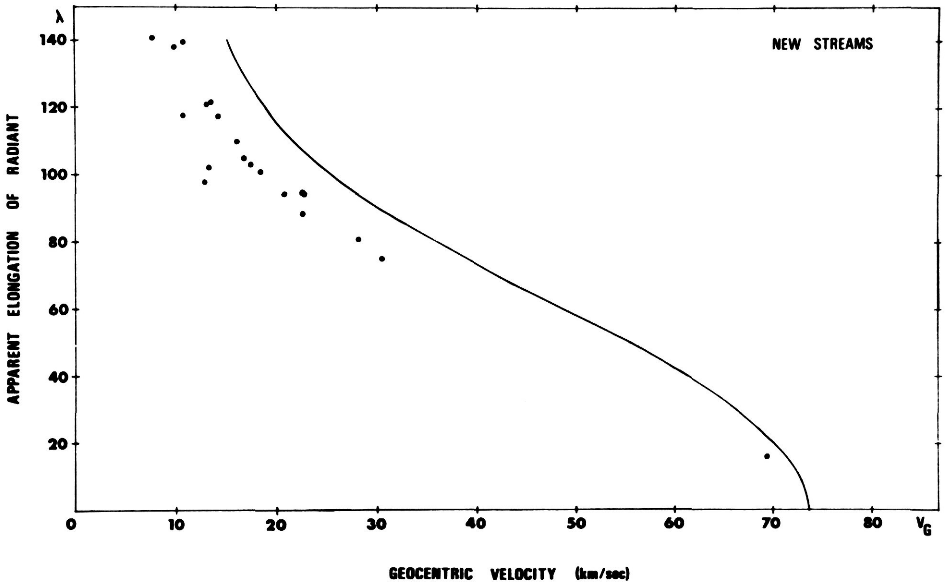
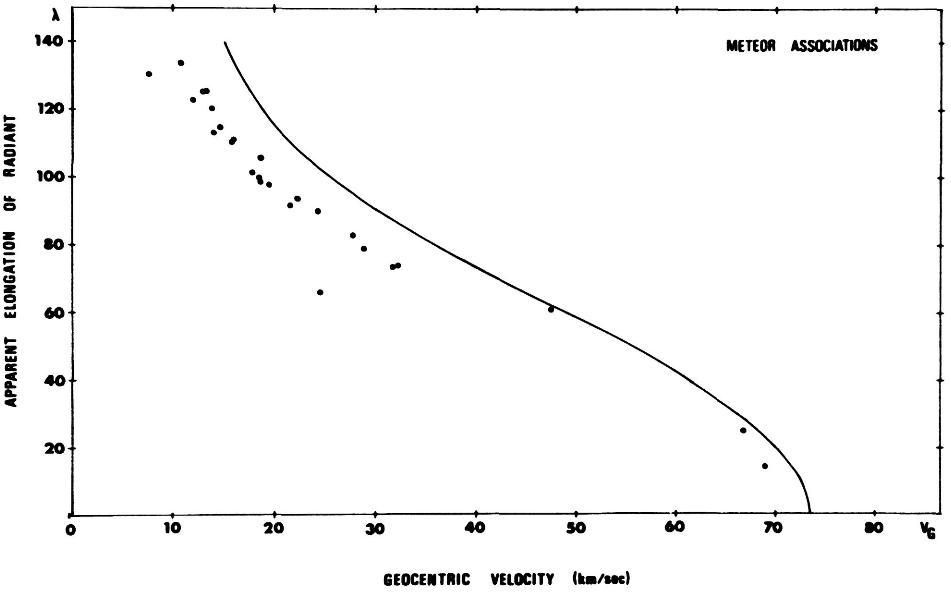


FIGURE 4.—Velocity-elongation diagram for the meteor associations of Jacchia and Whipple.



from the parabolic limiting curve at approximately $\lambda=60°$ and is displaced by about 5 km/sec with respect to the curve. It is evident from considerations of the geometry involved that members of the meteor streams plotted in the upper left-hand part of the diagrams are moving in direct, low-inclination orbits. These meteors are approaching the earth from the anti-apex direction and are catching up with us at relatively low velocities.

The velocity-elongation diagram for streams listed in Tables 4 and 5 is shown in Figure 3, from which it is apparent that the new streams detected by the two computer searches are, with only one exception, all of the low-inclination, low-velocity type mentioned above. Meteors belonging to these showers are obviously more difficult to observe, since only fairly large meteor masses will produce sufficient luminosity to be detected. Their shower identification is also difficult to establish, since the low geocentric velocity implies a diffuse radiant. It is therefore not surprising that these streams do not generally show up in the radiant lists of visual observers.

Meteor associations

Jacchia and Whipple (1961) attempted to classify into a number of groupings, or associations, meteor orbits not belonging to a recognized stream. The classification was based on orbital similarity. Of the 552 meteor orbits common to our study and that of Jacchia and Whipple, 161 were arranged in groupings or associations. A comparison of these associations with the unidentified streams in our search reveals five cases where the streams and associations have identical members and an additional five cases where an entire association (of Jacchia and Whipple) is included in one of our minor streams. These identifications, however, mainly involve streams and associations with only two or three members. Too much weight should therefore not be attached to them.

Although good agreement between the associations of Jacchia and Whipple and the minor streams of the computer search occurs in only a few cases, the statistical properties of these two groups are very similar. In the velocity-elongation diagram (Figure 4), we have plotted datum points for all the associations listed by Jacchia and Whipple and having three or more members in our sample. A comparison of Figures 3 and 4 clearly shows that the new streams found by either principle of classification have a tendency to cluster in the upper left-hand part of the velocity-elongation diagram.

Acknowledgments

This investigation was carried out mainly during two visits to the Harvard College Observatory and Smithsonian Astrophysical Observatory in 1963 and 1965. For the investigations, Drs. G. S. Hawkins, L. G. Jacchia, and R. B. Southworth very kindly placed at my disposal complete card sets of their meteor data. Their constant help and advice are gratefully acknowledged. The assistance of Mrs. S. Rosenthal has been invaluable in the reduction work.

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Abstract

A search for meteor streams was made among 865 precise photographic meteor orbits collected in the Harvard Meteor Program. An automatic computer program was utilized. In all, 80 meteor streams were detected. Of these, 21 represent 19 previously known, well-studied photographic meteor showers and 17 represent new meteor streams found by McCrosky and Posen and by Southworth and Hawkins. Five previously unstudied photographic streams with four or more members were discovered. Of these, three were identified with streams reported by visual observers.

Of the remaining streams, 8 have 3 members and 29 have only 2 members. About half the 2- and 3-member streams are believed to be spurious. A comparison of these streams with the meteor associations of Jacchia and Whipple indicate similar statistical properties, but few individual agreements are noticed.

Bertil-Anders Lindblad

2. A Computerized Stream Search Among 2401 Photographic Meteor Orbits

Introduction

The existence of a large number of weak meteor showers has been inferred by several observers from their numerous visual observations. Until recently, the photographic meteor data have not been sufficient to confirm or to refute these observations. The large samples now available of meteor orbits determined from photographic or radio data make a renewed study of the minor streams desirable.

New criteria for the definition of a meteor stream and computer techniques for meteor-stream detection have recently been proposed by Southworth and Hawkins (1963) and by Southworth (1968). Successful application of these techniques to radio meteor orbits has been reported by Hawkins, Southworth, and Rosenthal (1964), Elford, Hawkins, and Southworth (1964), and Forti (1968), and to photographic meteor orbits by Southworth and Hawkins (1963) and Lindblad (1970).

PREVIOUS STUDY.—Lindblad (1970) used the computer stream-detection technique in the analysis of a sample of 865 precisely reduced photographic orbits collected in the Harvard Meteor Program. The technique successfully detected and sorted out all the previously known photographic meteor streams for which more than one member was available in the sample. In addition, eight new meteor streams of more than four members were delineated. All these new streams were of low geocentric velocity and low inclination.

Present investigation

McCrosky and Posen (1961) have given fundamental data for 2529 photographic meteors recorded by the Baker Super-Schmidt cameras of the Harvard Meteor Program. The sample studied constituted about 70 percent of all meteors photographed from February 1953 to July 1954. It is the largest sample of photographic meteor orbits hitherto available and thus provides valuable material for a study of meteor streams. Of the meteors studied, 2059 were reduced by the graphical method (McCrosky, 1957). The sample included 355 meteor orbits reduced by Jacchia by a more accurate technique, as well as 115 meteors without orbital information.

PREVIOUS SEARCHES IN THE SAMPLE.—McCrosky and Posen (1961) identified and listed a number of meteors belonging to the familiar major showers. In an earlier study of essentially the same data, McCrosky and Posen (1959) had compared radiants, velocities, and dates and

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found seven new minor photographic streams. Of these, only two could be identified with previously known visual meteor streams. Since a stream search using classical methods of classification is very laborious, no exhaustive search was made in the McCrosky and Posen sample. Subsequently, Terent'eva (1965, 1968) analyzed a very large collection of photographic data, including those from the McCrosky and Posen sample.

PURPOSE OF PRESENT SEARCH.—Using the D-criterion for stream membership (Southworth and Hawkins, 1963), the present study concerns an exhaustive search among the orbits given by McCrosky and Posen. It differs from the previous stream search by Lindblad (pages 1–13) in that the data sample is larger but, at the same time, the errors in the orbital elements are larger. The errors in velocities and radiants, nevertheless are smaller than those obtained in visual meteor programs. Therefore, we felt that a stream search in the McCrosky and Posen sample would supply valuable new information about minor meteor streams and thus provide students with an up-to-date list of minor meteor streams and their orbits. If most of the more prominent showers reported by visual observers could be detected in the photographic data, the accuracy of the older visual data would be confirmed.

DATA PREPARATION.—Of the 2529 meteors listed by McCrosky and Posen, 115 were omitted, since no orbital information was available. An additional 13 meteors with orbital eccentricities $e \geq 2.0$ were also rejected. The sample under study thus consisted of 2401 meteors whose orbital elements were available on cards, together with the shower classification originally proposed by the authors. In the preparation of the input for the computer stream search, the cards were sorted in order of increasing inclination. Inclinations $i=90^\circ.0$ were not accepted by the program and were therefore altered to $i=89^\circ.9$. No other modifications were made in the original data.

D-criterion for stream membership

The computer stream-detection technique of Southworth and Hawkins (1963) is based on the intercomparison of different sets of orbital elements. In the search, each meteor orbit in a sample is compared with all others in the sample to find groups of similar orbits. This approach is particularly useful for detecting minor streams since only a few orbits are necessary for delineating a stream.

The use of a computer has two advantages: a large collection of data can be handled, and the search is objective. But the rejection level D_s must be set by the investigator, and firm rules must be laid down for this choice.

DETERMINATION OF REJECTION LEVEL D_s.—Southworth and Hawkins (1963) proposed that the rejection level D_s should vary inversely with the fourth root of sample size. For a sample of 360 precise photographic orbits, they used $D_s=0.20$. If N is sample size, we therefore have

$$D_s=0.20\times\left(\frac{360}{N}\right)^{\frac{1}{4}}. \tag{1}$$

Equation (1) has been tested by the present author on several data samples of precise photographic orbits. In general, agreement with conventional shower classification is good if D_s is assigned a value slightly lower than that given by equation (1). The following approximate rule may be recommended:

$$D_s=0.80\times N^{-\frac{1}{4}}. \tag{2}$$

It may be necessary to use a somewhat smaller value of D_s if the orbital data have appreciable observational or reductional errors.

For $N=2401$, equation (1) gives $D_s=0.125$, while equation (2) gives $D_s=0.114$. In a first test run of the McCrosky and Posen sample, $D_s=0.12$ was used. It was found, however, that at this rejection level several low-inclination meteor streams were not clearly separated. A new search at $D_s=0.115$ gave the desired separation for most of these streams, and this value was therefore adopted.

Discussion of stream search

The sample of orbits was divided by the search at $D_s=0.115$ into 1049 stream meteors and 1352 sporadic meteors. Thus, 43 percent of the meteor population was in streams. The percentage of stream meteors and associations, as defined by

TABLE 1a.—*Durations, radiants, and geocentric velocities of previously known photographic meteor streams*

Provisional stream no.	Stream name	Duration	α_R	δ_R	V_G
42	Northern δ Arietids	Dec 8–Jan 2	54	25	17
52	Southern Virginids	March 12–27	185	- 2	28
60	Southern ι Aquarids	July 19–Aug 6	320	-15	35
110	Southern ι Aquarids	Aug 5–22	348	-10	41
61	Southern Taurids Northern Taurids	Sept 19–Nov 21	40	13	31
62	Northern Virginids	Feb 18–March 12	173	5	36
76	Northern χ Orionids	Dec 4–13	83	26	28
78	Northern ι Aquarids	Aug 21–Sept 20	354	1	31
92	Piscids	Aug 31–Nov 2	10	6	27
105	Pegasids	Oct 29–Nov 12	344	19	16
108	α Capricornids	July 15–Aug 10	304	-10	25
122	α Capricornids	Aug 4-9	317	- 7	28
109	Southern χ Orionids	Dec 7-14	85	16	28
171	Northern δ Aquarids	Aug 5-25	347	1	40
186	Geminids	Dec 4-16	111	32	37
196	Southern δ Aquarids	July 21–Aug 8	340	-16	43
202	Draconids	Oct 9	276	49	21
216	Quadrantids	Jan 2–3	229	49	42
217	Lyrids	April 21–22	271	34	47
220	Hyperbolic Perseids	Aug 9–13	-	-	-
221	Perseids	Aug 8–15	46	57	60
223	σ Hydrids	Dec 13–15	129	1	59
228	Orionids	Oct 16–Nov 7	95	16	67
230	Hyperbolic Orionids	Oct 14–29	-	-	-
231	ε Geminids	Oct 16–27	102	27	70

conventional methods of classification based on geocentric quantities, is normally about 50 percent. Previous computer stream search have given very nearly the same percentage (Lindblad, 1970). The lower stream contribution found here is probably due to the larger errors in the orbital elements.

The number of streams at $D_s = 0.115$ was 198. In an endeavor to present the data in some orderly fashion, we shall first list streams previously detected by conventional techniques and then those previously detected by other computer searches, and finally, several new streams that have been identified with visual streams. Several new comet-meteor associations will also be presented.

PREVIOUSLY KNOWN PHOTOGRAPHIC STREAMS.—Tables 1a and 1b present radiants and orbits of 21 previously known photographic meteor streams detected in the search. The mean orbital elements do not differ appreciably from those published in other lists of meteor stream orbits determined by the Harvard Meteor Program (McCrosky and Posen, 1959; Jacchia, 1963). It follows that orbital data obtained by the graphical reduction procedure of McCrosky and Posen are sufficiently accurate for use in a computer stream search.

It should be observed that the mean radiant and geocentric velocity listed by the computer program are obtained directly from the mean orbit of the stream. These quantities may therefore differ slightly from those obtained by averaging of individual meteor data.

The showers listed in Tables 1a and 1b may be regarded as well confirmed. They have been

TABLE 1b.—*Orbital elements of previously known photographic streams*

No.	Stream name	q	a	e	i	ω	Ω	π	Harvard serial no.
42	Northern δ Arietids	0.857	2.420	0.634	2°.1	228.0	262.6	130.6	5527 5552 5573 5752 5772 5878 5953 5970 6023 9438 9486 9498 9841 9895
52	Southern Virginids	0.431	2.027	0.783	0.3	287.0	356.4	283.4	6786 6816 10353
60	Southern ι Aquarids	0.266	3.967	0.925	0.0	121.5	304.0	65.5	3355 3406 3407 8235
110	Southern ι Aquarids	0.119	3.662	0.959	12.6	143.9	321.8	105.7	3619 3658 3784 8178 8318 8410 8483 8624
61	Southern Taurids Northern Taurids	0.330	1.991	0.828	3.3	118.8	28.7	147.5	4455 4498 4507 4546 4556 4574 4666 4701 4732 4747 4754 4764 4819 4830 4832 4862 4866 4883 4891 4907 4912 4928 4966 4975 4999 5003 5019 5022 5074 5115 5124 5147 5176 5180 5195 5244 5257 5298 5341 5346 5347 5353 5371 5380 5388 5417 5419 5425 5429 5499 5511 8796 8803 8811 8836 8849 8855 8886 8945 8954 8956 8971 8990 8998 9004 9015 9016 9037 9041 9063 9074 9077 9104 9121 9150 9158 9182 9185 9210 9216 9238 9240 9246 9249 9257 9265 9276 9280 9314 9328 9331
62	Northern Virginids	0.234	2.637	0.912	3.5	308.0	333.8	281.8	6496 6798 10200 12237
76	Northern χ Orionids	0.472	2.220	0.787	2.5	281.0	258.3	179.3	5620 5886 9400 9674
78	Northern ι Aquarids	0.326	2.000	0.830	4.0	299.7	161.4	101.1	3663 3886 4516
92	Piscids	0.525	2.864	0.808	1.5	273.6	190.1	103.7	3864 4369 4391 4476 4478 4505 4520 4531 4544 4582 4605 4684 4728 4767 4774 4839 4967 4977 4987 5064 8767 8777 8790 8800 8830 8832 8838 8872 8899 8922 8930 9030 9134
105	Pegasids	0.966	3.512	0.718	6.8	200.2	227.0	67.2	5367 5370 5373 5396 9107
108	α Capricornids	0.592	2.524	0.760	7.1	267.9	125.4	33.3	3379 3382 3385 3386 3387 3405 3408 3410 3411 3416 8026 8063 8148 8149 8225 8304 8334 8668
122	α Capricornids	0.497	2.573	0.807	8.7	279.0	133.4	52.4	8146 8147 8368
109	Southern χ Orionids	0.471	2.387	0.790	6.9	100.6	79.1	179.7	5529 5537 5795 9416 9488 9661 9745 16777
171	Northern δ Aquarids	0.085	2.102	0.956	20.7	330.8	140.5	111.3	3573 3574 3610 4219 8168 8210 8371 8441 8610
186	Geminids	0.140	1.466	0.902	23.2	324.2	260.2	224.4	5533 5543 5566 5581 5601 5605 5614 5618 5624 5637 5640 5644 5648 5655 5659 5667 5673 5677 5681 5683 5690 5701 5705 5709 5711 5714 5720 5729 5734 5759 5764 5777 5785 5789 5797 5814 5817 5824 5862 5868 5891 5893 5897 5899 5901 5911 5917 5922 5926 5928 5933 5939 5946 5952 5964 5980 5991 6005 6021 8645 9390 9418 9421 9425 9451 9454 9510 9547 9611 9656 9709 9719 9725 9742 9749 9771 11401
196	Southern δ Aquarids	0.074	2.765	0.972	28.4	151.6	307.1	98.7	3360 3399 3421 3424 3447 3450 3463 3472 3487 8187 8238 8254 8344
202	Draconids	0.999	3.330	0.700	25.0	177.0	196.0	13.0	8943 8951
216	Quadrantids	0.974	2.612	0.618	72.4	170.5	282.8	93.3	9902 9907 9928 9942 9945 9946 9952 9954 9962 9964 9966 9974 9975 9980 9983 9986 9988
217	Lyrids	0.879	25.812	0.956	78.6	217.2	31.6	248.8	3217 3218 3271 7444 7447
220	Hyperbolic Perseids	0.958	-30.601	1.065	113.0	153.4	138.6	292.0	8374 8418 8431 8435 8437 8492 8494 8501 8516 8532 8536
221	Perseids	0.934	22.527	0.920	113.2	147.9	138.7	286.6	8324 8330 8348 8383 8401 8420 8424 8444 8452 8463 8469 8496 8512 8518 8555 8567 8599 8658 8719 8726
223	σ Hydrids	0.230	11.525	0.980	125.0	124.0	82.0	206.0	8648 9660
228	Orionids	0.570	16.720	0.931	163.9	83.4	29.2	112.6	5001 5006 5015 5023 5039 5076 5079 5083 5093 5101 5112 5119 5127 5129 5183 5185 5208 5210 5282 9090 9097 9099 9258
230	Hyperbolic Orionids	0.617	- 9.537	1.135	164.1	75.0	28.0	103.0	4789 4811 4876 4922 4936 5013 5041 5095 5097 5102 5140 5145 5153 5155 5157 5163 5165 5196 5260 5327 9079
231	ε Geminids	0.770	14.895	0.940	173.0	236.7	207.5	84.2	4889 5063 5309 9082

discussed in the literature and will therefore only be briefly commented on here. It will be seen that the Southern ι Aquarids and α Capricornids are split into one July and one August stream. The Perseids and the Orionids are divided into an elliptical and a hyperbolic branch. This division is obviously a spurious result caused by the large errors in the graphical reduction procedure. The Piscid stream (no. 92) is included in Tables 1a and 1b since it was originally believed that this stream was related to the Andromedids. The Andromedid stream has recently been shown to be much more extensive than formerly believed (Hawkins, Southworth, and Stienon, 1959); however, the fairly high geocentric velocity and early date of appearance of stream 92 preclude the possibility of a relation to the Andromedids. Stream 92 includes all members of a previously detected shower: the ε Piscids (Lindblad, 1971).

A number of streams were split into a northern and a southern branch. This phenomenon had previously been detected in the Harvard data for the Taurids, ι Aquarids, and δ Aquarids. Our study indicates a similar splitting of the χ Orionids. In the case of the Virginid stream the precision of the orbital data is not sufficient to decide if the observed separation into two branches is significant. The δ-Arietid stream (McCrosky and Posen, 1959) also consists of a northern and a southern branch. Only two members of the southern branch are present in the McCrosky and Posen sample, however, and the computer search incorporated these in the northern branch. Of their 47 new meteor associations, Jacchia and Whipple (1961) list 4 more cases of a northern and a southern stream component. In the stream catalog of

TABLE 2a.—*Durations, radiants, and geocentric velocities of streams detected in previous computer searches (Southworth-Hawkins = Listed in "Statistics of Meteor Streams"; Lindblad 865 = Listed in "A Stream Search Among 865 Precise Photographic Meteor Orbits")*

Provisional stream no.	Stream name	Duration	α_R	δ_R	V_G	Identification
8	σ Leonids	March 21–May 13	195	- 5	20	Southworth–Hawkins Hoffmeister's Virginids McIntosh 103 (θ Virginids)
20	κ Aquarids	Sept 11–28	338	- 5	20	Lindblad 865-10 Denning 268 McIntosh 299
45	μ Ophiuchids	Aug 10	267	-14	15	Southworth–Hawkins McIntosh 182
83	Northern λ Virginids	April 4–15	210	-10	32	Lindblad 865-16 McIntosh 114
85	Southern λ Virginids	May 5–6	210	-18	25	Lindblad 865-16
90	ρ Geminids	Jan 15–23	112	31	21	Southworth–Hawkins
98	θ Ophiuchids	June 4–16	266	-28	30	Southworth–Hawkins McIntosh 184
102	Southern χ Geminids	Jan 23–Feb 7	122	13	21	Southworth–Hawkins
119	χ Scorpiids	May 27–June 20	246	-12	23	Lindblad 865-17 (θ Librids) McIntosh 147
126	θ Cetids	Oct 19–21	22	-11	19	Lindblad 865-38 McIntosh 28?
137	Northern χ Geminids	Jan 19–21	127	34	23	Southworth–Hawkins
152	ω Ursae Majorids	May 7–June 5	184	47	16	Southworth–Hawkins
160	ψ Ursae Majorids	April 10–13	188	59	15	Southworth–Hawkins
167	θ Herculids	Aug 6–9	260	30	18	Southworth–Hawkins
168	τ Herculids	May 19–June 14	228	40	18	Southworth–Hawkins Comet 1930 VI
188	ϕ Bootids	April 16–May 12	240	51	16	Southworth–Hawkins
191	α Bootids	April 14–May 12	218	19	23	Southworth–Hawkins Denning 169?
203	γ Bootids	April 13–15	215	36	25	Southworth–Hawkins

Terent'eva (1965, 1968), several more cases are reported. In nearly all cases, we have to deal with low-inclination orbits, in which there is a shift of 180° in the argument of perihelion ω and in the longitude of the ascending node Ω between the two branches, the radiants moving nearly parallel to the ecliptic, one south of it and the other north.

It should be mentioned that the computer search failed to separate the northern and southern branches of the Taurid meteor stream. A similar result was obtained in the previous search of 865 orbits.

STREAMS DETECTED IN PREVIOUS SEARCHES.—Tables 2a and 2b list 18 new photographic meteor streams that first were detected in the computer searches of Southworth and Hawkins (1963) and Lindblad (1971) and now are confirmed in this study.

In the previous study of 865 orbits, 13 possible new photographic meteor streams were listed in Table 6 (page 8). These were considered to be the most significant of the newly detected streams. It is encouraging to note that 12 of these were also detected in this study as separate streams (Table 2a). The single exception was the ϵ-Piscid stream, which, as previously mentioned, was included in our Piscid stream (no. 92). Hardly any doubt can therefore exist about the reality of the streams listed in Tables 2a and 2b. A comparison with the radiant lists of Denning (1899) and McIntosh (1935) gave a number of identifications with visually observed showers. These are listed in Table 2a.

In the comparison, a critical attitude was taken toward the radiants listed by Denning. His belief in long-persisting stationary radiants often led him to combine unrelated stream radiants in an arbitrary way. Denning's radiants were therefore accepted only if on inspection of the radiant list a short, well-defined period of stream activity was found. As an additional criterion, Denning's remarks as to the velocity classification (slow, fast) were compared, when available, with the photographically determined velocity.

On comparison of our new streams with the previous computer search listings, it was found that the mean radiant had sometimes shifted by

TABLE 2b.—*Orbital elements of streams previously detected by computer searches*

No.	Stream name	q	a	e	i	ω	Ω	π	Harvard serial no.
8	σ Leonids	0.753	2.349	0.663	0.7	247.5	28.2	275.7	3015 3246 7058 7133 7158 7201 7240 7287 7303 7336 7356 7372 7480 7520 7664 10406 11190 11955 11976
20	κ Aquarids	0.814	3.196	0.744	1.8	235.6	178.0	53.6	4292 4432 4492 4624 4679
45	μ Ophiuchids	0.980	2.420	0.595	2.5	204.5	137.0	341.5	8394 8415
83	Northern λ Virginids	0.343	2.630	0.870	2.0	295.0	19.5	314.5	7073 7333
85	Southern λ Virginids	0.686	6.705	0.895	3.5	72.0	224.5	296.5	11912 11947
90	ρ Geminids	0.708	2.197	0.673	5.0	252.3	297.7	190.0	6162 6179 6338
98	θ Ophiuchids	0.405	2.797	0.852	4.7	108.0	258.0	6.0	7726 7782 7808 7899
102	Southern χ Geminids	0.693	2.390	0.710	4.0	72.0	130.5	202.5	6329 6393
119	χ Scorpiids	0.679	3.112	0.767	6.0	256.7	73.9	330.6	7754 7823 7924 10584 12138 12341 12368 12436 12478 12508 12517
126	θ Cetids	0.783	1.760	0.555	8.5	67.0	27.0	94.0	4918 4997
137	Northern χ Geminids	0.595	1.830	0.675	9.5	268.5	300.0	208.5	6260 6296
152	ω Ursae Majorids	0.998	3.893	0.740	12.3	186.7	59.3	246.0	7529 7694 7745
160	ψ Ursae Majorids	0.984	1.805	0.455	14.0	203.0	21.5	224.5	7179 7265
167	θ Herculids	1.005	3.113	0.667	16.7	194.3	135.0	329.3	8244 8363 8369
168	τ Herculids	0.970	2.695	0.633	18.6	204.2	71.9	276.1	3335 4103 4106 4108 4112 7692 7820 12142 12161 12355 12378 12398 12470 12513
188	ϕ Bootids	0.949	1.248	0.237	19.3	225.8	40.5	266.3	3212 7379 7485 7577 7651 11848
191	α Bootids	0.753	2.647	0.706	18.0	246.9	36.2	283.1	3239 7291 7385 7439 7506 7643 11174 11863
203	γ Bootids	0.818	3.790	0.775	27.0	235.5	24.0	259.5	7261 7331

several degrees. This occurred particularly among minor streams with only a few members in the sample under study. In future discussions, a number of these streams should therefore be renamed. To simplify identification, however, most of the provisional stream names used in previous papers have been retained in Tables 2a and 2b.

Again a number of streams are split by the search into a northern and a southern branch. In Table 2b, we note this for the λ Virginids and χ Geminids. The existence of two λ-Virginid branches is, however, somewhat open to doubt on account of the large differences in g and a. An inspection of the argument of perihelion ω and longitude of node Ω of the individual stream members shows that two branches also exist in the σ-Leonid and χ-Scorpiid streams. The southern branch of the χ Scorpiids was identified with the visual ω^2-Scorpiid shower (McIntosh no. 146), the northern branch, with the visual χ-Scorpiid shower (McIntosh no. 147).

The largest new stream detected in previous computer searches is a rather poorly defined one radiating from Leo and Virgo during the period February-May. This stream is often referred to as the σ Leonid since Southworth and Hawkins (1963) found a mean radiant near σ Leonis. Although the computer search did not distinguish between the two components, an inspection of the argument of perihelion of individual members showed that the stream is composite, with one northern and one southern branch. The northern branch, with activity in March-May, has a mean radiant near θ Virginis. The southern branch, with activity in April and May, has a mean radiant near ψ Virginis. Activity in February and March from a radiant near δ Leonis (Table 3a) adds additional complexity to the picture.

NEW PHOTOGRAPHIC STREAMS.—After identification of the well-confirmed photographic streams (Tables 1 and 2), a large number of previously unknown streams remained to be studied. Of these, 108 had 2 members, and 43 had 3 members. We feel that about half of these streams are chance associations. Unfortunately, there is no way of concluding which streams are spurious. We therefore rejected all except those for which an identification with a well-studied visual shower was immediately obvious. These identifications are listed in Tables 3a and 3b.

A total of 18 streams that had 4 or more members each and that were not already listed in Tables 1 and 2 remained. Attempts to identify these possible new photographic streams with previously observed visual streams by Denning and McIntosh were successful in some cases. These identifications are listed in Tables 3a and 3b. Remaining nonidentified streams have been rejected.

The photographic δ-Leonid stream is active at the same time as the Leonid-Virginid stream. The δ-Leonid radiant is identical with a prominent radiant of the same name in Denning's catalog. Our photographic μ-Sagittarid stream is identical with a major shower of the same name listed by McIntosh (1935). A study of the orbit suggests an association with Comet Lexell. The α Lyrids and ζ Draconids are listed as prominent showers by Denning. They are active at the same time as the κ Cygnids and are often confused with this shower. An alternative interpretation of the two α-Scorpiid streams is to consider them as southern branches of the ϕ-Ophiuchid stream (no. 123). In a similar way the ο Serpentids may be interpreted as a northern branch of the θ Ophiuchids (no. 98).

In our search, the Cyclid stream was incorporated into a vast agglomerate of short-period, low-inclination orbits (stream 1, with 61 members). Inspection of radiant coordinates and orbital elements of individual members of this stream revealed very large scatter. Stream 1 was therefore rejected. A subsequent substream search at $D = 0.10$ produced a Cyclid stream with 15 members, the orbital elements of which are similar to those given by Southworth and Hawkins (1963).

Hoffmeister's ecliptical streams

Inspection of radiant catalogs published by visual observers suggests a rather confused grouping of radiants all along the ecliptic. An attempt to systematize this picture has been made by Hoffmeister (1948), who reported that a major contribution to the meteor-stream complex came from a few short-period, low-inclination streams. These were referred to as the "ecliptical streams." Hoffmeister listed six ecliptical streams, of which three, the δ-Aquarid, Taurid, and Geminid, are now well-established photographic streams. The remaining three, listed in Table 4, have not been previously recognized as photographic streams. A comparison with our Tables 1–3 produced the possible identifications listed in Table 4.

TABLE 3a.—*Durations, radiants, and geocentric velocities of new photographic streams*

Provisional stream no.	Stream name	Duration	α_R	δ_R	V_G	Identification
21	δ Leonids	Feb 5–March 19	159	19	23	Denning 120 or 129
28	δ Cancrids	Jan 13–21	126	20	28	Denning 100
31	Piscids	Sept 25–Oct 19	26	14	29	Denning 17 (η Arietids)
59	α Scorpiids	May 9–12	247	-24	35	McIntosh 157
81	α Scorpiids	April 11–May 5	235	-21	34	Denning 190?
73	μ Sagittariids	June 22–July 6	268	-15	23	McIntosh 173 Denning 204 (υ Ophiucids) Comet 1770 I
123	ϕ Ophiuchids	May 3–8	247	-18	38	McIntosh 160
129	α Triangulids	Nov 7–12	22	30	21	Denning 20
144	μ Virginids	April 13–May 12	221	- 5	29	Denning 166?
146	o Serpentids	June 9–25	274	-11	30	McIntosh 178 Denning 204 (υ Ophiucids)
174	η Serpentids	June 25–July 3	278	- 2	25	McIntosh 191 Denning 211
204	α Lyrids	Aug 4–13	282	42	23	Denning 219
207	ζ Draconids	Aug 20–25	269	59	24	Denning 198
225	Lyncids	Sept 27–28	110	48	66	Denning 84?
232	ζ Arietids	Aug 13–25	49	14	71	Denning 154?

TABLE 3b.—*Orbital elements of new photographic streams*

No.	Stream name	q	a	e	i	ω	Ω	π	Harvard serial no.
21	δ Leonids	0.643	2.618	0.747	6.2	259.0	338.1	237.1	2982 4012 6391 6399 6440 6458 6460 6467 6484 6766 6776 6915 6918 6940 6971 6995 10164 10168 10193 10208 10270 10303 12690 12773
28	δ Cancrids	0.448	2.273	0.800	0.3	282.6	296.4	219.0	6069 6081 6176 6189 6254 6258 6292
31	Piscids	0.399	2.062	0.797	3.4	290.8	199.1	129.9	4560 4793 4854 4856 4870 4938 8952 9025 9070
59	α Scorpiids	0.212	2.235	0.905	3.5	132.0	229.5	1.5	7610 12089
81	α Scorpiids	0.189	2.097	0.893	2.3	136.7	216.3	353.0	7248 7474 11935
73	μ Sagittariids	0.680	2.862	0.757	5.5	257.5	95.3	352.8	4147 4169 4175 7944
123	ϕ Ophiuchids	0.133	2.170	0.937	10.0	322.0	44.0	6.0	7575 11832 11903
129	α Triangulids	0.784	3.257	0.757	9.7	238.0	227.5	105.5	5335 5339 5382 5392
144	μ Virginids	0.477	3.116	0.831	9.9	280.0	35.0	315.0	3021 3250 7272 7348 7583 7622 12076
146	o Serpentids	0.430	2.895	0.847	13.0	284.2	85.8	10.0	4143 4181 12541 12576
174	η Serpentids	0.606	2.165	0.715	15.5	268.5	97.0	5.5	12713 12864
204	α Lyrids	0.958	3.437	0.720	29.7	207.7	134.7	342.4	8143 8227 8476
207	ζ Draconids	1.015	2.820	0.640	33.0	183.5	149.5	333.0	3633 3813
225	Lyncids	0.770	76.970	0.990	136.5	152.5	184.5	337.0	4622 4683
232	ζ Arietids	0.973	17.905	0.945	172.5	19.5	326.0	345.5	3804 8526

TABLE 4.—*Comparison of Hoffmeister's ecliptical streams and new photographic streams*

Name	Duration of stream	q	a	e	i	ω	Ω	π	α	δ	V_G
Virginids (Hoffmeister)	March 1–May 10	0.48	1.53	0.69	1°.9	286°	13°	299°	200°	- 6°	
σ Leonids (8)	March 21–May 13	0.75	2.35	0.66	0.7	248	28	276	195	- 5	20
Piscids (Hoffmeister)	Aug 16–Oct 8	0.40	1.43	0.72	3.5	296	169	105	0	+ 4	
Northern ι Aquarids (78)	Aug 21–Sept 20	0.33	2.00	0.83	4.0	300	161	101	354	+ 1	31
Piscids (31)	Sept 25–Oct 19	0.40	2.06	0.80	3.4	291	199	130	26	14	29
Sco-Sgr system (Hoffmeister)	April 20–July 30	0.47	1.77	0.73	6.0	106	263	9	270	-30	
θ Ophiuchids (98)	June 4–16	0.41	2.80	0.85	4.7	108	258	6	266	-28	30

The identity between Hoffmeister's Virginid and our Leonid-Virginid stream is of particular interest. Table 4 compares our mean Leonid-Virginid orbit with the visual Virginid orbit determined by Hoffmeister (1948). The radiant at $\alpha = 195°$, $\delta = -5°$ differs but little from the visual Virginid radiant reported by him. The period of activity, 21 March-13 May, is also in agreement with his data. Hoffmeister's orbit was based on visual estimates of velocities. In view of the uncertainties inherent in this method, the discrepancies in q and a must be regarded as not significant.

Hoffmeister's Scorpius-Sagittarius system closely resembles our θ-Ophiuchid stream. Inspection of Table 4 shows good agreement in all orbital elements. His Piscid stream is more difficult to identify. Our Northern ι-Aquarid stream probably is a September apparition of the Piscids, while our Piscid stream 31 probably represents an October display of Hoffmeister's stream. Another possibility is that our Piscid stream (no. 92) is identical with Hoffmeister's Piscids.

Comet-meteor associations

Hasegawa (1958) has published a general index of the expected theoretical radiant points of meteors associated with comets. A comparison of our new meteor-stream radiants with the theoretical radiants yielded several probable associations. Orbital elements of meteor streams and associated comets are compared in Table 5.

One new stream, the μ-Sagittariid, moves in an orbit similar to that of Comet 1770 I (Lexell). Since the comet orbit crosses the earth's orbit twice, two meteor showers can occur, one in June-July and one in December. The nearest

TABLE 5.—*Comet-meteor associations found in McCrosky and Posen sample*

Name	Observed/ predicted date	q	a	e	i	ω	Ω	π	α	δ	V_G
μ Sagittariids	June 22–July 6	0.680	2.862	0.757	5°.5	257°.5	95°.3	352°.8	268°	-15°	23
Comet Lexell (1770 I)	July 5	0.674	3.153	0.786	1.6	224.3	132.0	356.3	272	-21	21
τ Herculids	May 19–June 14	0.970	2.695	0.633	18.6	204.2	71.9	276.1	228	40	18
Schwassmann-Wachmann (3) (1930 VI)	June 8	1.011	3.09	0.672	17.4	192.3	76.8	269.1	218	45	14
Monocerotids	Dec 12–17	0.175	52.24	0.994	31.5	131.0	82.5	213.5	104	10	42
Comet Mellish (1917 I)	Dec 15	0.190	27.64	0.993	32.7	121.3	87.5	208.8	103	9	40
ζ Arietids	Aug 13–25	0.973	17.905	0.945	172.5	19.5	326.0	345.5	49	14	71
Schmidt-Temple (1862 II)	Aug 21	0.981	-	1.000	172.1	27.2	327.8	355.0	49	13	72

approach to the earth's orbit does not occur at the node but at node –32° and node –60°, respectively. Table 5 shows that the μ-Sagittariid stream is detected at node –37°, in agreement with predictions. The December apparition is not detected in our study, probably because the radiant is too far south. Tentative associations between Comet 1770 I and various minor meteor streams of June and December have been proposed by several authors (Terent'eva, 1964; Nilsson, 1963, 1964). However, none of these streams agrees very well with the orbit of Comet 1770 I.

A tentative association between the τ-Herculid stream and Comet 1930 VI (Schwassmann-Wachmann) has been proposed by Southworth and Hawkins (1963). The larger data sample now available has made it possible to delineate clearly the τ-Herculid orbit. Inspection of Table 5 suggests good agreement in all orbital elements, and the proposed comet-meteor relation may now be considered very probable. The meteor stream associated with Comet 1930 VI was observed visually in Japan in 1930 (Nakamura, 1930). The computed radiant and orbit of this stream agree reasonably well with our τ-Herculid orbit.

Two members of the December Monocerotid stream are present in the McCrosky-Posen meteor sample (meteors 6040 and 9557). A comparison of the mean Monocerotid orbit with Comet 1917 I (Mellish) indicates close correspondence in all orbital elements, and this association must now be regarded as fairly certain. Our identification of the Monocerotids with Comet 1917 I receives support from the tentative connection suggested by Whipple (1954) between this comet and Harvard meteors 2313 and 2405.

A fourth comet-meteor association, the ψ Arietids with Comet 1862 II (Schmidt-Temple), is fairly probable, although the meteor-stream orbit is based on only two photographic meteors. Particular attention is here drawn to the very small earth-comet orbit distance of 0.028 a. u.

Porter (1952) gives a list of 19 theoretical radiants for 17 ecliptical comet orbits, observed after 1700, that approach the earth's orbit to within 0. 1 a. u. Of these radiants, 11 can easily be seen from the Northern Hemisphere, and 8 of these correspond to well-known meteor showers. The detection of the μ-Sagittariid, τ-Herculid, and Monocerotid photographic meteor streams add three more comet-meteor associations to Porter's 1952 list, leaving only one comet (1743 I) without observed meteors.

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Abstract

A computer stream search has been made among 2401 photographic meteor orbits. The resulting meteor streams are presented in tabular form. For known photographic streams, the mean orbital elements, as determined by the search, are similar to those previously obtained by conventional methods of stream classification.

Many new photographic meteor streams have been detected by the search. Some have been identified with visual showers listed by Denning, McIntosh, and Hoffmeister. The extensive Leonid-Virginid photographic stream is identified with Hoffmeister's Virginid stream. Identifications with other ecliptical currents reported by Hoffmeister are also suggested.

Several streams are split into a northern and a southern branch, with their orbital planes symmetrical with respect to the plane of the ecliptic.

Four streams move in orbits similar to those of well-known comets: the μ Sagittariid is associated with Comet Lexell (1770 I), the τ Herculid very probably with comet Schwassman-Wachmann (1930 VI), the December Monocerotid with Comet Mellish (1917 I), and the ζ Arietid with Comet Schmidt-Temple (1862 II). Porter's list of comets approaching the earth's orbit to within 0.1 a.u. gives the first three mentioned meteor-cometary associations as predicted but not observed. The addition of these three to the list implies that ten of eleven theoretical radiants listed by Porter as observable in the Northern Hemisphere have now been detected.

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