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Southern Hemisphere Meteor Stream Determinations

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Abstract

Meteor orbits have been deduced from radio observations of meteor trails carried out at Adelaide (latitude 35° S.), using a combined multi-station continuous wave and pulse radar system operating at 27 MHz. Observations were made for one week each month during the period December 1968 to June 1969, and also during October 1969. The orbits of 1667 meteors have been determined down to a limiting radio magnitude of +8. The data have been systematically searched for stream meteors, and the significance of minor associations has been appraised. Altogether 40·4% of the orbits were found to be associated with at least one other orbit, and 29·8% with two or more. Numerous minor streams with high inclination and low eccentricity have been found at deep southern declinations from December to March, with little activity in this quarter during June and October. In addition to confirming several previously established cometary associations, a comprehensive search has indicated that 34 of the meteor associations found may be related to 17 comets. Associations between several long-period comets and low-eccentricity high-inclination streams appear to be indisputable, and they confirm the origin of at least some of the 'toroidal group' meteors, previously a matter of some doubt.

1. Introduction

The Adelaide radio meteor system has evolved over a number of years from that first described by Robertson *et al.* (1953). Its use for the measurement of individual meteor orbits was first undertaken by Nilsson (1964*b*) to limiting magnitude $M_R = +6$. Modifications to the system, including increases in transmitter power and the provision of two additional receiving sites, have substantially improved the resolution. The survey presently described is to date the only one in the Southern Hemisphere to measure individual meteor orbits to limiting magnitude $M_R = +8$.

In its current form the Adelaide radio meteor system consists of a 1·5 kW c.w. transmitter on 26·8 MHz and, at the same site, a 65 kW peak pulse transmitter on 27·5 MHz, with pulses of 8 μs duration at a p.r.f. of 200 s^{-1} (Weiss and Elford 1963). Reflections from a minimum of three and a maximum of five points along the trail are used to determine the radiant and velocity. A long-distance outstation enables us to make occasional measurements of reflection point separations as large as 16 km, although the majority of reliably determined separations are of the order of 6 km or less. Fig. 1 shows the ground station configuration and reflection point geometry. The equipment is also used to measure winds and wind shears in the meteor region, enabling account to be taken of these factors in the determination of radiant and velocity data from the radio echoes.

Observations were made for one week each month from December 1968 to June 1969 and a further one week in October 1969. The 1667 orbits discussed in this paper were obtained during the periods 9–16 December, 21–23 January, 10–17 February, 16–22 March, 7–14 June and 15–19 October. It should be noted that all tables throughout the paper list the orbital elements and radiant in the following units: a and q in a.u.; i, ω, Ω, π, α and δ in degrees; and V_∞ in km s^{-1}.

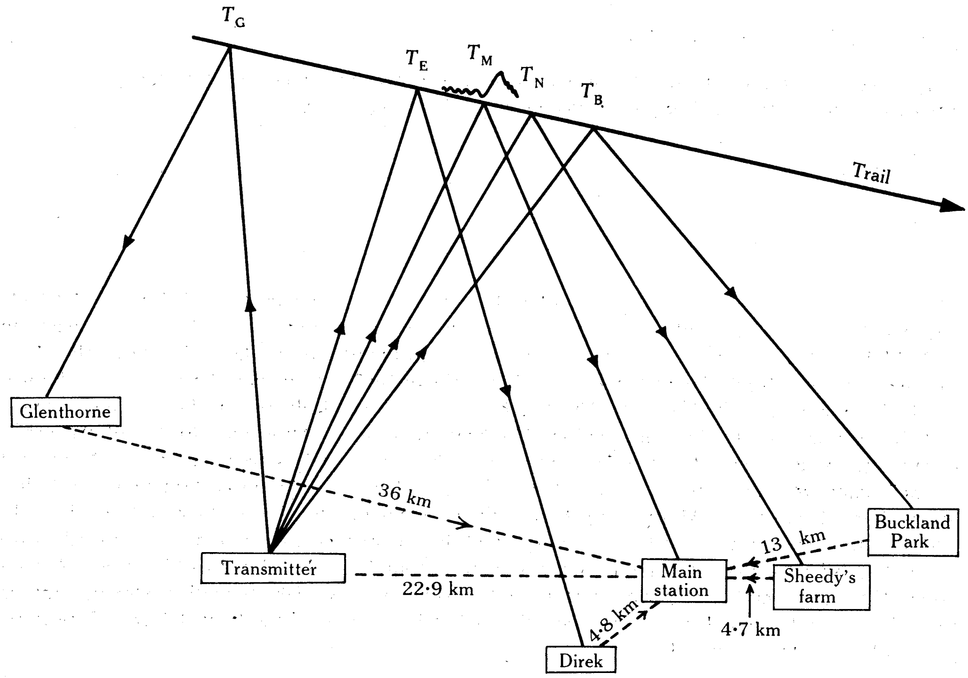

Fig. 1. Schematic diagram (not to scale) of the site locations and geometry of the Adelaide radio meteor system. The times T_G, T_E, T_M, T_N, and T_B refer to the passage of the meteoroid through the specular reflection points for each site. Signals from the outstations are transmitted to the main station via FM links. The form of a typical signal is shown at the time T_M.

2. Meteor Stream Detection

A major problem in the classification of meteor orbits concerns the differentiation of stream meteors from the sporadic background. While photographic meteors of certain streams may sometimes be identified by their characteristic spectra, light intensity profiles and beginning heights (McKinley 1961; Ceplecha 1968), classification of radio meteors is entirely dependent upon the comparison of orbital elements or radiant data. For the present purposes, a meteor stream is defined as a significant concentration of orbits in orbit space.

The scatter between the measured orbital elements of stream meteors will result from measurement errors as well as from the true differences between the orbits. The effect of the former can be estimated and, for radio meteors, is relatively large. The true differences depend upon the nature and duration of the dispersion mechanism.

(a) *Association tests for stream meteors*

Several workers have attempted to find some objective criterion for testing the association of two meteor orbits (Southworth and Hawkins 1963; Nilsson 1964*b*; Sekanina 1970; Lindblad 1971). Indeed such a criterion, with the assistance of a computer, is almost essential for the comparison of the large number of meteors detected by a radio survey such as the present one.

Southworth and Hawkins (1963) devised an association test which amounts to a measure of the distance between two orbits in a 5-dimensional space, based upon the five independent elements specifying the orbit, suitably weighted. In order that two meteors A and B may be considered to be associated, the distance $D(\mathrm{A},\mathrm{B})$ between their orbits in this space must be less than some predetermined value D_s. The distance $D(\mathrm{A},\mathrm{B})$ is expressed as

$$D(\mathrm{A},\mathrm{B}) = \left(\sum_{j=1}^{5} c_j^2\{C_j(\mathrm{A})-C_j(\mathrm{B})\}^2\right)^{\frac{1}{2}}, \tag{1}$$

where the C_j are suitable independent functions of the orbital elements, and the c_j are normalizing functions which should be inversely proportional to the expected standard deviation of the corresponding C_j in a stream.

There is a fundamental difference between the application of the D criterion to two meteor orbits to test for association within certain limits, and the application of the same criterion to the members of a stream. Stream meteors may be considered as being either directly or serially associated. For direct association, all members of the stream must lie within a certain distance D_m of the mean orbit for that stream. For serial association, it is only necessary that each member of the stream is associated with at least one other member of the stream to within some standard distance D_s. The latter case thus represents a form of 'chaining' where two orbits, which would not be found associated according to the first test, are linked by an intermediate orbit.

There are two reasons for favouring the serial association test over the direct test: (1) serial association is the appropriate association test to apply when the dispersion of the stream is due to any mechanism that acts differentially on meteors of different mass, as may occur in the case of the Poynting–Robertson effect; (2) the serial association test has the advantage of not requiring any *a priori* knowledge of the orbit of a meteor stream and is therefore a suitable method for searching for new streams. A stream search procedure based on the concept of serial association has been developed by Southworth (1963) and its application has been discussed by Lindblad (1971*a*).

Sekanina (1970) followed the Southworth and Hawkins (1963) method for determining D, but he modified their requirement for associated orbits to differ by less than a predetermined D value. Instead Sekanina proposed that an iterative procedure be used to determine the mean orbit, and that a stream be defined by the statistics of the D distribution around the mean orbit, making allowance for contamination of the sample by the sporadic background.

The D criterion was developed by Southworth and Hawkins (1963) initially for studying orbits determined from photographic observations, where the precision of measurement is such that the real scatter in the values of the elements greatly exceeds the random deviations due to observational errors. On the other hand, Nilsson (1964*b*) was concerned with orbital data obtained only with the radio technique, where the limited precision can cause relatively large scatter between orbital elements due to the errors in measurement alone. As a consequence, Nilsson assumed identical orbits for all members of a stream, and his association test required agreement between each of the orbital elements of two meteors in turn to within two standard deviations of the measurement error for that element.

In the present analysis we have applied both tests to the sample and have found benefit from using the D criterion. Our results, while still only of the same accuracy as those of Nilsson (1964*b*), have delineated numerous streams of undoubted reality in which the dispersion greatly exceeds that due to measurement error alone. It is evident that these streams become increasingly significant at fainter limiting magnitudes.

(*b*) *Choice of association limits*

The major problem in seeking meteor orbit associations is to decide what should be regarded as acceptable differences between meteor orbits classed as members of the same stream. Streams are formed at different times, and the members gradually disperse under the influence of both the spread in energies of the member particles at stream formation and the subsequent action of various external perturbing forces. Members of old streams are therefore expected to show greater dispersion of orbital elements than members of streams of more recent origin. However, a stream is characterized by an increased density of orbits compared with adjacent regions of orbit space. If the association limits are based upon stream dispersion alone, random observational errors will move more true-stream meteors outside the accepted limits of stream membership than the number of sporadics which, through chance or error, will be included in the stream classification. On the other hand, increasing the association limits to include probable measurement error may recover most of the stream meteors but will also increase the probability of inclusion of spurious meteors in the sample.

Southworth and Hawkins (1963) applied the D criterion to known streams in a sample of 359 precise photographic orbits and deduced that for a sample of this size the rejection level D_s should be $0\cdot20$. They also indicated that the value of D_s should vary inversely as the fourth root of the sample size. Lindblad (1971*b*) applied the D criterion to several samples of precise photographic orbits and concluded that a good working rule for the value of D_s is $0\cdot80\,N^{-\frac{1}{4}}$, where N is the number of meteors in the sample.

In general, the distribution of orbits in the phase space defined by the D criterion is far from isotropic. If there are sufficient meteors in the sample, a more refined test should take account of the gross variations in population density. In practice it is sufficient to carry out several stream searches at different values of D_s, typically $0\cdot20$, $0\cdot15$ and $0\cdot10$. It is usually found that in any sample of meteor orbits there is a strong concentration of orbits of low inclination, and these orbits become associated into an extensive pseudostream at the higher values of D_s (Lindblad 1971*a*). Real stream structure in the low inclination complex can be tested by further searching at lower values of D_s.

(*c*) *Significance of small groups*

When the D criterion is applied to a set of meteor orbits there will be a relatively large number of streams containing two, three or four members. Some of these will be genuine but weak streams, while others will be the spurious result of chance associations.

Southworth and Hawkins (1963) and Nilsson (1964*b*) determined the likelihood of spurious streams in their data by searching for streams in equivalent sets of artificial data that were constructed in each case by shuffling and re-assigning the appropriate orbital elements. 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 that already contain a significant proportion of streams. Nilsson concluded that the majority of associated pairs that he found in his original data were due to chance, while larger associations were probably significant. Lindblad (1971*b*) estimated that, within a sample of 2401 photographic orbits, about 50% of the streams with two or three members were chance associations at a D_s value of 0·115.

Neither of the above estimates took into account the probability of detection of the streams nor the observed variation in the density of orbits in space. Thus a pair of associated orbits, detected in a region of orbit phase-space that has a low probability of observation, will be of greater significance than a pair of associated orbits from a readily observable region. This is illustrated clearly by reference to the spurious streams detected by Southworth and Hawkins (1963) in their artificial sample. They found eight associations: five pairs, and one each with three, four and five orbits. The larger associations each had eccentricities near 0·59 and the pairs had higher values. Mean inclinations, apart from one pair with a value of 10°, were all 6° or less. We may infer from their test that any association in their data with higher inclination is likely to be significant, even if only for a pair of meteors.

3. Present Systematic Stream Search

The data obtained in the present survey have been systematically searched for streams in two ways:

(1) The data were sorted on each orbital element in turn, with the allowable differences for association set to slightly more than two standard deviations of the measurement error in each case. This resulted in 32% of the meteors being associated; a value which drops to 21% when associations of pairs only are excluded.

(2) The data were also searched for streams using the D criterion method of Southworth and Hawkins (1963), setting $D(\mathrm{A,B}) = 0{\cdot}10$ as the association limit, and then augmenting these data with additional streams detected with the value of $D(\mathrm{A,B})$ set at 0·20. The latter were checked for any duplication of the $D < 0{\cdot}10$ streams and also for associations in which 'chaining' had become obvious. This search found 40% of the meteors to be associated, or 30% excluding pairs.

Generally the same streams were detected by both methods, although in some cases there were minor variations in subgrouping. As the latter test is apparently more sensitive, the results from that test are presented here. It is interesting to note that proportionately less pairs were detected by the D criterion method, mainly due to the inclusion of some of the pairs into larger streams. Associations of three or more meteors are listed in Table 1. Pairs may well be significant at high inclinations, but are probably less so for orbits close to the ecliptic. These are listed in the table given in the Appendix. We note that the minimum value of D chosen for the stream search is close to the value of 0·125 derived from the empirical expression given by Lindblad (1971*b*) and quoted in Section 2*b*.

The present stream search based on the D criterion method classified 30% of the meteors into streams of three or more members. Nilsson (1964*b*) estimated that in his survey of the orbits of 2200 radio meteors about 25% were associated into streams.

This estimate is probably conservative as Nilsson based his association test on individual orbital elements, and we have shown that in the case of the present survey this stream search method detected 8–9% less members of streams than the D criterion method. Lindblad (1971*b*) applied the D criterion method to 2401 photographic meteor orbits and found that 37% were associated into streams after rejecting chance associations amongst two-member and three-member groups, while Southworth and Sekanina (1973) estimated that about 30% of 12600 orbits of faint radio meteors were members of streams.

Table 1. Associations of three or more meteors

Ident.	Mean date	No.	$1/a$ (a.u.$^{-1}$)	q (a.u.)	e	i °	ω °	Ω °	α °	δ °	V_∞ (km s^{-1})	$\bar{D}$(M, N)	Stream
						December							
12·01	13	4	0·69	0·09	0·93	2·0	331	261	111	+23	38	0·05	
12·02	14	6	0·37	0·33	0·85	7·1	117	82	95	+18	32	0·14	
12·03	14	3	0·22	0·74	0·77	9·4	65	82	71	+05	23	0·12	
12·04	12	5	0·33	0·50	0·83	20·4	95	80	88	+02	30	0·13	
12·05	14	20	0·74	0·13	0·90	18·2	327	261	112	+30	36	0·12	Gem
12·06	15	7	0·44	0·97	0·56	57·3	344	82	135	−63	35	0·19	
12·07	13	6	0·84	0·98	0·16	69·5	0	81	141	−43	37	0·14	
12·08	13	3	0·94	0·98	0·08	74·5	1	82	145	−45	39	0·05	
12·09	13	3	0·13	0·19	0·98	39·9	130	82	106	+06	42	0·08	Mon
						January							
1·01	22	3	0·34	0·98	0·64	74·3	7	122	160	−63	43	0·13	Car
						February							
2·01	13	3	0·48	0·36	0·82	4·5	246	144	316	−21	31	0·07	
2·02	15	6	0·54	0·27	0·85	0·1	125	147	164	+06	32	0·06	
2·03	14	3	0·21	0·60	0·87	18·0	98	325	320	+07	29	0·10	
2·04	15	3	0·49	0·19	0·90	7·8	315	326	169	+09	35	0·05	
2·05	12	5	0·48	0·61	0·69	8·1	86	143	148	+25	24	0·08	
2·06	14	3	0·68	0·20	0·86	12·2	137	145	167	−02	33	0·05	
2·07	14	4	0·62	0·23	0·85	20·4	313	325	174	+16	33	0·07	
2·08	14	3	1·11	0·04	0·96	33·6	13	326	284	−16	37	0·09	
2·09	12	3	0·14	0·86	0·93	49·9	43	143	133	−50	35	0·10	
2·10	14	3	0·11	0·98	0·89	47·2	12	145	110	−65	32	0·05	
2·11	13	5	0·34	0·98	0·67	48·4	354	145	99	−76	31	0·13	
2·12	14	3	0·76	0·99	0·25	54·1	3	146	155	−77	31	0·05	
2·13	14	9	0·42	0·93	0·60	62·0	33	145	152	−65	37	0·19	
2·14	14	47	0·56	0·93	0·44	61·9	340	145	179	−83	36	0·39	
2·15	13	4	−0·08	0·95	0·93	70·2	330	144	250	−86	44	0·13	
2·16	12	5	0·44	0·98	0·56	118·0	171	323	241	+15	59	0·13	
2·17	13	3	1·24	0·46	0·43	141·5	322	323	225	+01	54	0·11	
2·18	14	11	0·44	0·82	0·62	2·1	299	144	346	−24	18	0·23	
						March							
3·01	19	7	0·59	0·18	0·89	1·8	42	359	338	−08	35	0·08	
3·02	19	3	0·08	0·75	0·91	7·3	62	178	159	−05	23	0·09	
3·03	19	5	0·61	0·23	0·86	19·4	312	358	203	+03	33	0·07	
3·04	18	11	0·47	0·98	0·53	55·3	347	178	51	−81	34	0·22	
3·05	19	10	0·10	0·98	0·87	58·3	346	178	50	−78	38	0·17	
3·06	18	5	0·63	0·88	0·41	65·7	57	177	195	−74	37	0·17	
3·07	19	3	0·49	0·65	0·65	57·3	83	179	184	−58	36	0·10	
3·08	17	3	0·04	0·93	1·00	61·9	28	177	154	−73	40	0·13	
3·09	19	3	0·05	0·76	0·90	59·3	58	178	173	−60	40	0·09	
3·10	17	4	0·35	0·95	0·67	73·6	332	177	332	−79	43	0·11	
3·11	19	3	0·71	0·93	0·34	85·2	317	179	297	−72	45	0·11	
3·12	19	7	0·37	0·94	0·62	92·8	29	178	241	−71	50	0·22	
3·13	21	4	0·22	0·99	0·76	95·9	353	181	281	−72	53	0·12	
3·14	19	6	0·22	0·98	0·62	121·6	13	178	262	−56	60	0·18	
3·15	20	3	0·85	0·66	0·43	137·4	97	179	250	−43	57	0·11	
3·16	19	4	0·12	0·42	0·93	141·8	282	359	240	−04	62	0·13	

Table 1 (*Continued*)

Ident.	Mean date	No.	$1/a$ (a.u.$^{-1}$)	q (a.u.)	e	i °	ω °	Ω °	α °	δ °	V_∞ (km s^{-1})	$\bar{D}$(M, N)	Stream
						June							
6·01	11	4	0·44	0·52	0·77	1·3	97	260	262	−25	26	0·04	
6·02	10	3	0·33	0·93	0·68	14·0	216	79	234	+20	18	0·11	
6·03	13	3	0·28	0·04	0·98	2·4	18	82	47	+18	42	0·05	
6·04	11	9	0·54	0·02	0·99	18·0	14	81	44	+19	43	0·09	
6·05	11	32	0·36	0·08	0·96	17·4	28	81	49	+23	41	0·19	Ari
6·06	11	4	0·67	0·02	0·99	30·9	11	80	39	+19	43	0·06	
6·07	12	6	0·65	0·06	0·96	38·2	203	261	48	+09	41	0·09	
6·08	10	4	0·87	0·11	0·90	33·5	152	259	297	−34	35	0·10	
6·09	11	13	0·54	0·15	0·90	39·5	324	80	289	−06	38	0·19	
6·10	9	4	0·39	0·37	0·86	43·3	292	79	280	+06	37	0·09	
6·11	10	5	1·10	0·14	0·84	66·3	333	80	303	+03	37	0·11	
6·12	11	6	0·51	0·12	0·92	65·3	214	261	47	−02	43	0·13	
6·13	11	3	0·12	0·29	0·96	68·1	297	80	290	+05	46	0·09	
6·14	12	3	0·20	0·90	0·81	171·0	317	261	4	−04	68	0·13	
6·15	11	3	0·15	0·27	0·59	145·3	6	80	349	+10	48	0·11	
6·16	13	4	0·03	0·42	0·98	166·4	280	80	323	−09	65	0·12	
6·17	11	8	0·19	0·99	0·79	177·7	165	80	354	−01	69	0·20	
6·18	13	3	0·14	0·51	0·89	177·8	266	262	16	+06	65	0·12	
						October							
10·01	16	3	0·24	0·47	0·90	8·2	96	23	28	+03	31	0·05	
10·02	17	3	0·31	0·43	0·86	8·9	104	24	32	+04	31	0·03	
10·03	17	3	0·15	0·92	0·85	138·2	34	23	101	00	66	0·13	
10·04	17	4	0·29	0·51	0·84	145·0	94	23	87	+08	63	0·15	
10·05	17	6	0·14	0·65	0·85	161·8	76	24	94	+14	67	0·18	
10·06	17	3	0·41	0·99	0·58	171·6	352	23	115	+17	68	0·11	
10·08	17	7	−0·38	0·63	1·26	147·7	70	24	87	+08	71	0·17	
						Associations common to more than one month							
						Broad streams: Single intersection							
S·01	1·22 2·10–16	1 5	0·19	0·75	0·82	13·9	62	140	124	−05	23	0·13	
						[R.A. ≈ 124° + 0·5(⊙ − 140)°]							
S·02	12·16 1·21–23	1 3	0·47	0·17	0·91	9·4	167 132	84 121	121 141	+19 +08	43 35	0·13	
S·03	1·21–22 2·12–13	2 3	0·14	0·95	0·79	165·9	204	316	220	−07	70	0·15	
						Double Intersections							
D·01	6·09–14 10·15–19	6 49	0·58	0·30	0·82	7·1	69 129	81 24	65 44	+27 +11	30 31	0·15	ζ-Per S. Tau
D·02	2·12 6·10–13	1 6	0·60	0·39	0·76	0·6	54 114	323 261	308 271	−21 −24	30 28	0·09	
D·03	12·14–16 6·10–11	2 2	0·50	0·61	0·67	54·2	276 277	79 83	288 210	+25 −62	34 37	0·13	
D·04	12·13 6·12	2 1	0·22	0·57	0·86	144·8	88 98	81 81	142 8	−02 +21	64 63	0·11	
D·05	12·12 6·11–14	1 2	0·34	0·54	0·82	0·4	91 84	80 81	81 81	+24 +23	27 27	0·03	

Thus there appears to be remarkably close agreement amongst estimates of the fraction of meteors that are classified as members of streams by the *D* criterion method and, further, there is only a marginal change in this fraction over a large range of masses from photographic to faint radio meteors. Poole and Kaiser (1972) have studied range–time records of radar meteor echoes on an objective basis and observed that in any set of random samples of 4 h sections of records, at least half exhibited noticeable activity from one or more unidentified radiants within the sporadic distribution. They concluded that the range–time structure derived from a large number of weak radiants that might not be resolvable using the stream search techniques described in Section 2*a*.

(*a*) ***Particular streams and possible cometary associations***

Geminid Meteor Stream

The Geminid meteor stream is one of the most intense streams observed in the Northern Hemisphere, and it has been well studied in a number of surveys. It has a compact radiant and thus provides a useful check on the accuracy of radiant determination by the radio technique. Table 2 compares our values for the mean radiant and orbit of the Geminids observed at Adelaide during December 1968 with results from earlier observations by other workers. The agreement is generally good.

Table 2. Radiant and orbit of Geminids

Ref.*	N	α	δ	V_∞	$1/a$	q	e	i	ω	Ω
S68	20	112·3	+30·2	36·2	0·74	0·13	0·90	18·2	326·7	261·3
W54	13	112·7	+32·4	36·4	0·73	0·14	0·90	23·9	324·4	261·2
MP61	72	111·3	+32·5	36·3	0·71	0·14	0·90	23·1	324·2	260·2
JW61	20	111·4	+32·5	36·2	0·74	0·14	0·90	23·3	324·3	260·2
SH63	16	112·6	+32·3	36·3	0·73	0·14	0·90	23·3	324·1	261·4
N64B	22	109·4	+30·4	34·2	0·79	0·15	0·88	17·4	325·1	259·8
KL67	401	111·4	+32·6	36·0	0·76	0·14	0·89	23·7	325·8	259·6

* References: S68, present survey; W54, Whipple (1954); MP61, McCrosky and Posen (1961); JW61, Jacchia and Whipple (1961); SH63, Southworth and Hawkins (1963); N64B, Nilsson (1964*b*); KL67, Kashcheev and Lebedinets (1967).

The mean declination is somewhat lower than that observed in the majority of cases, and the inclination also correspondingly lower. The low value of declination has been attributed by Nilsson (1964*b*) to the unfavourable location of the radiant for observation from Adelaide. As a result there would be larger than normal observational errors which, on the basis of the comparison of the present results, would appear to have some systematic bias towards lower declinations. This bias is difficult to explain if the radiant is virtually a point source, but would be relatively easily explained in terms of the variation in sensitivity of the Adelaide system at low elevations, if the Geminid radiant at magnitudes +6 to +8 were extended. A relatively weak subsidiary radiant at lower declinations would not affect Northern Hemisphere results greatly but could significantly influence observations from Adelaide.

The mean R.A. for the twenty Geminids of association 12·05 is

$$\alpha = 112\cdot3^\circ + 1\cdot1(\alpha_\odot - 261\cdot3)^\circ,$$

which corresponds more closely to the majority of measurements than Nilsson's (1964*b*) determination of

$$\alpha = 109\cdot8^\circ + 1\cdot1(\alpha_\odot - 260\cdot1)^\circ.$$

The mean daily motion of the radiant coincides with that observed by Nilsson and is greater than that measured by Weiss (1959) and Kashcheev and Lebedinets (1967).

However, little reliance can be placed on our measurement, once again because of the poor observability of the radiant at Adelaide. Nevertheless, the results do indicate that there are no serious systematic errors in the reduction procedure, and they provide a lower limit to our expectations of accuracy for radiants more suited to observation from Adelaide.

Association 12·15 lies close to the Geminid radiant but the velocity measurement seems significantly higher. Although small, the possibility of measurement error in the reduction cannot be ruled out entirely in this case.

Differences between the declinations of associations 12·01, 12·10 and 12·11, and the mean declination of the Geminid radiant are too great to be attributable to error alone. These associations apparently represent a weaker diffuse stream probably associated with the Geminids but with lower inclination.

Webster *et al.* (1966) reported the detection at Sheffield of a second 'early' radiant associated with the Geminids, which had a similar declination but a value of right ascension approximately 15° less, which agrees well in R.A. with association 12·02 of the present survey. It is most interesting in this regard to note the similarities between the Geminids and the 11 Canis Minorid stream recently discovered by Hindley and Houlden (1970). Table 3 compares both visual and photographic data for this stream with data for the Geminids, considering the latter with negative inclination and the nodes interchanged.

Table 3. Geminids and 11 Canis Minorids

Stream	α	δ	V_∞	$1/a$	q	e	i	ω	Ω
11 Canis Minorids	115	+12	—	—	0·04	—	89	158	78
	115	+13	38	0·53	0·08	0·96	33	151	80
Geminids	111	+32	36	0·73	0·14	0·90	−22	147	80

As Hindley and Houlden (1970) noted, the new stream is only the second such found for which $q < 0\cdot1$ a.u., the other being the δ-Aquarid/Arietid stream. Several other associations with similarly small perihelion distance have been detected amongst radio meteors by the present survey and by Kashcheev and Lebedinets (1967). Nevertheless, in view of the rarity of this type of orbit, the similarity in the alignment of the nodes and arguments of perihelion of the Geminids and 11 Canis Minorids suggests that a relation between the two streams cannot be discounted. It is possible too that other stream activity during the same period with radiants in the same quarter of the sky (Tables 11 and 12 below), including the Monocerotids, may have a common origin. Alternatively the streams may have been generated by members of a comet group. Groups of this type are not unknown: in particular, the Kreutz group of sun-grazing comets, as the name suggests, also have small perihelion distances (Marsden 1967).

Hindley and Houlden (1970) suggested a possible association of the 11 Canis Minorids with comet Mellish 1917 I, although searching has failed to find any comet associated with the Geminids. Kresáková (1974) has examined all available catalogues of photographic meteor orbits and has delineated two distinct stream components intermediate between the orbits of the Geminids and comet Mellish 1917 I. Component A corresponds to the Monocerotid stream described below, while component B has an orbital period much closer to that of the Geminids. Because of the compact distribution of the Geminid orbits, Kresáková ruled out any possibility of the intermediate streams implying an evolutionary link between the orbits of the Geminids and comet Mellish. It is suggested instead that the source of the Geminids, if related to the comet, is more likely to have undergone disruption from the parent body as a whole prior to the detachment of the meteoroids currently observed.

Table 4 lists the orbital elements of comet G. Kirch 1680. The radiant data are those predicted by Hasegawa (1962) for a stream associated with this comet. The general similarity of this comet's orbit to that of the Geminids may also be more than a coincidence. The differences of approximately 30° in longitude of perihelion and inclination could be accounted for by a relatively small perturbation to the comet's orbit at some distance from perihelion, in view of its unusually small perihelion distance.

Table 4. Comet G. Kirch 1680

Ident.	α	δ	V_∞	a	q	e	i	ω	Ω
1680	133	+21	51	426·7	0·006	0·999	60·7	351	272

Nilsson (1964*a*) reported observation during September 1961 of the Sextanid meteor stream also observed by Weiss (1960) during 1957, and he noted its similarity to the Geminids. A search amongst the present October data has not revealed any Sextanids.

Three associated pairs were found in October with small perihelion distances and perihelion longitudes within 30° of that for the Monocerotids. These associations are listed in Table 5. Associations 10·14 and 10·15 show similarities which confirm their significance. The values of V_∞ are similar to those for the Monocerotids, although the similarity between the Monocerotid orbit and that of comet Mellish 1917 I (Table 11) suggests that yet another comet may have given rise to associations 10·14, 10·15 and possibly 10·12.

Table 5. Three October associations

Ident.	α	δ	V_∞	$1/a$	q	e	i	ω	Ω
10·12	55	+18	28	1·24	0·16	0·80	2·6	152	24
10·14	56	+03	41	0·49	0·14	0·92	45·7	143	24
10·15	58	+12	44	0·64	0·04	0·98	48·8	162	23

Virginids

Only minor activity associated with the Virginid stream was observed during March. McKinley (1961) listed the dates, between which meteors of this stream may be detected, as 5 March to 2 April. Table 6 lists three associated pairs and one unassociated meteor from the present survey that occurred between these dates, together with other observations of this stream for comparison. Two of these associations have higher inclinations than previously observed. Of particular interest is the close similarity between the March association 3·03 and association 2·07 in February, also listed, and between these orbits and the lower inclination Virginids.

If these higher inclination streams are classified as a branch of the Virginids, our observations extend the dates of detection forward to 12 February.

Although differing in inclination by about 15°, association 2·07 corresponds very well in π and q to the Northern Virginid stream listed by Lindblad (1971*b*) as being detected from 18 February to 12 March.

Nilsson (1964*b*) suggested a possible connection between his March Virginid data and an association of three meteors observed in December. Association 12·13 in the present survey, again only for a pair of orbits, corresponds quite well to the March associations 3·22 and 3·24 except for smaller size of orbit, and is particularly close to 3·03. Nilsson's December association similarly has a smaller mean orbit than his Virginids.

Table 6. Radiant and orbit of Virginids

Ident.	Ref.*	N	α	δ	V_∞	$1/a$	q	e	i	ω	Ω
33201	S	1	190	−04	34	0·40	0·30	0·88	1	299	357
3·17	S	2	183	−03	30	0·32	0·41	0·86	1	105	177
3·22	S	2	197	+04	31	0·50	0·32	0·84	14	300	358
3·24	S	2	201	+09	34	0·44	0·29	0·86	24	302	358
3·03	S	5	203	+03	33	0·61	0·23	0·86	19	312	358
2·07	S	4	174	+16	33	0·62	0·23	0·85	20	313	325
12·13	S	2	237	−08	31	0·85	0·23	0·80	18	44	261
(Vir)	W54	4	182	+04	32	0·25	0·42	0·90	6	284	354
(Vir)	MP61	5	179	+01	29	0·46	0·44	0·80	1	285	351
(Vir)	JW61	3	176	00	29	0·37	0·45	0·83	2	102	170
(Vir)	N64B	3	189	−04	34	0·42	0·26	0·89	3	304	355
(Vir)	KL67	9	188	+01	31	0·51	0·36	0·82	6	297	356
(Vir)	L71B	4	173	+05	36	0·38	0·23	0·91	4	308	334

* References: S, present survey; W54, Whipple (1954); MP61, McCrosky and Posen (1961); JW61, Jacchia and Whipple (1961); N64B, Nilsson (1964*b*); KL67, Kashcheev and Lebedinets (1967); L71B, Lindblad (1971*b*).

Arietids

Six associations were detected during June with radiants and velocities near the generally accepted values for the Arietid stream. As can be seen from Table 7, four of these correspond reasonably well to observations by other workers, while two (6·07 and 6·12) have significantly lower declinations. The latter two must be considered real since each has six members. Good agreement in longitude of perihelion as well as size and shape of orbits suggest that they are genuinely connected with the Arietids. No evidence of the progressive increase in inclination with passage through the stream noted by Lovell (1954) was found in this survey. However, the considerable spread in inclination found by other workers is extended even further by our observations.

Hyperbolic Streams

Altogether eight associations between meteors with hyperbolic orbits have been found in the present survey. Four of these are within probable measurement error of the parabolic limit for closed orbits, but the remainder are more strongly hyperbolic and seem unlikely to be entirely attributable to error. Nevertheless, similarity between some of these associations and adjacent elliptic streams suggests common

Table 7. Radiant and orbit of Arietids

Ident.	Ref.*	N	α	δ	V_∞	$1/a$	q	e	i	ω	Ω
6·03	S	3	47	+18	42	0·28	0·04	0·98	2·4	18	82
6·04	S	9	44	+19	43	0·54	0·02	0·99	18·0	14	81
6·05	S	32	49	+23	41	0·36	0·08	0·96	17·4	28	81
6·06	S	4	39	+19	43	0·65	0·02	0·99	30·9	11	80
6·07	S	6	48	+09	41	0·65	0·06	0·96	−38·2	23	81
6·12	S	6	47	−02	43	0·51	0·12	0·92	−65·3	34	81
(Ari)	L1	—	44	+22	38	0·67	0·10	0·94	18·0	29	77
(Ari)	L2	—	43	+24	39	0·62	0·09	0·94	21·0	29	77
(Ari)	DG60	6	50	+26	41	0·75	0·04	0·97	46·0	19	89
61·6·1	N64B	7	47	+25	44	0·44	0·04	0·98	38·9	20	85
61·6·2	N64B	8	46	+26	40	0·67	0·06	0·96	33·4	23	85
(Ari)	BF66	52	36	+26	38	0·36	0·09	0·93	31·3	27	73
(Ari)	KL1	380	43	+23	39	0·60	0·10	0·94	18·7	30	77
(Ari)	KL2	18	52	+25	40	0·60	0·08	0·96	22·8	25	87

* References and notes: S, present survey; L1, 1950 data of Lovell (1954); L2, 1951 data of Lovell (1954); DG60, Davies and Gill (1960); N64B Nilsson (1964*b*); BF66, Baker and Forti (1966); KL1, mean data of Kashcheev and Lebedinets (1967); KL2, data for 17–20 June of Kashcheev and Lebedinets (1967).

origins and does not favour the possibility of interstellar origin. Babadzhanov and Kramer (1967) drew similar conclusions from observations of hyperbolic meteors amongst the Perseids. Seven of the present associations are between pairs of meteors only, although two of the pairs probably belong to the one stream. The remaining association is between seven orbits all of which are hyperbolic. Table 8 compares the orbital elements of association 2·37 with the nearby association 2·15 of elliptic orbits.

Table 8. Hyperbolic and elliptic associations in February

Ident.	N	α	δ	V_∞	$1/a$	q	e	i	ω	Ω
2·15	4	250	−86	44	0·08	0·95	0·93	70·2	330	144
2·37	2	224	−85	49	−0·23	0·94	1·24	76·0	337	144

The main complex of observed hyperbolic associations occurred in October and seems to be related to the Orionid stream. Six Orionids were observed in this survey, and the mean orbit found for this stream is in good agreement with observations by other workers (see Table 9).

Table 10 compares the orbital elements for the October hyperbolic associations with the mean elements for the Orionids. Associations 10·09 and 10·10 were both detected on the same day and the degree of eccentricity of the orbits, if due to recent perturbation, could be related. The agreement in ω and Ω of 10·08 with the hyperbolic Orionids of Lindblad (1971*b*) is close.

Hajduk (1970) has studied the structure of the Orionid and η-Aquarid meteor stream, and has found that the Orionid stream is filamentous with filament diameters of the order of 10^6 km. Similarities between the Orionids and the less well-observed η-Aquarids appear to confirm the associations of these streams with comet Halley.

Table 9. Radiant and orbit of Orionids

Ident.	Ref.*	N	α	δ	V_∞	$1/a$	q	e	i	ω	Ω
10·05	S	6	94	+14	67	0·14	0·65	0·85	161·8	76	24
(Ori)	W54	2	95	+16	66	0·16	0·54	0·92	162·9	88	29
(Ori)	MP61	48	95	+15	68	0·02	0·58	1·01	162·8	80	31
(Ori)	JW61	5	95	+16	68	0·06	0·57	0·96	164·4	82	29
(Ori)	SH63	12	96	+16	68	0·05	0·57	0·97	164·9	83	29
(Ori)	N64B	6	97	+14	65	0·16	0·50	0·92	160·3	91	32
(Ori)	BF66	7	95	+16	65	0·26	0·56	0·83	165·0	88	27
(Ori)	KL67	61	93	+16	66	0·21	0·57	0·88	164·2	86	25
(Ori)	L1	23	95	+16	67	0·06	0·57	0·93	163·9	83	29
(Ori)	L2	21	—	—	—	−0·10	0·62	1·14	164·1	75	28

* References and notes: S, present survey; W54, Whipple (1954); MP61, McCrosky and Posen (1961); JW61, Jacchia and Whipple (1961); SH63, Southworth and Hawkins (1963); N64B, Nilsson (1964*b*); BF66, Baker and Forti (1966); KL67, Kashcheev and Lebedinets (1967); L1, Lindblad (1971*b*); L2, hyperbolics from Lindblad (1971*b*).

Table 10. October hyperbolic associations and Orionids

Ident.	N	α	δ	V_∞	$1/a$	q	e	i	ω	Ω
10·05	6	94	+14	67	0·14	0·65	0·85	161·8	76	24
10·07	2	90	00	66	−0·05	0·68	1·04	132·9	67	24
10·08	7	87	+08	71	−0·38	0·63	1·26	147·7	70	24
10·09	2	89	+06	78	−1·23	0·72	1·89	147·1	55	25
10·10	2	90	+15	79	−1·10	0·68	1·75	164·5	59	25

It would seem that the associations 10·09 and 10·10 are the most hyperbolic meteors ever found to be related to a meteor stream associated with a periodic comet. These associations indicate that strongly hyperbolic meteors observed at Earth may be the result of recent perturbations and need not imply an interstellar origin. Possibly the hyperbolic meteors have resulted from collisions between two or more large Orionids (see Section 3*d* below).

Monocerotid Stream

Although no Monocerotids were found to be associated by the systematic stream searches, three meteors were observed with radiants and velocities corresponding to this stream. One of these meteors is slightly hyperbolic, but the mean orbit is not. Agreement between present observations and those of past surveys is good, as shown in Table 11. The orbit of comet Mellish 1917 I is also given for comparison. Included in the table are two associations, 60·12·9 and 61·12·2, detected by Nilsson (1964*b*) in two successive years. The inclinations are 10°–15° lower than the Monocerotid stream but in other respects the characteristics of the streams are very similar.

Association 12·02 of the present survey has a radiant close to that of Nilsson's (1964*b*) associations 60·12·9 and 61·12·2 but the orbital elements (Table 12) clearly show that this association is related to, and possibly the same as, the μ-Geminids of Sekanina (1973*a*).

Table 11. Radiant and orbit of Monocerotids

Ident.	Ref.*	N	α	δ	V_∞	$1/a$	q	e	i	ω	Ω
12·09	S	3	106	+06	42	0·13	0·19	0·98	39·9	130	82
(Mon)	W54	2	103	+08	43	—	0·19	1·00	35·0	128	82
(Mon)	WH59	—	103	+08	43	—	0·19	1·00	35·2	128	82
(Mon)	SH63	1	102	+08	44	0·05	0·16	0·99	39·8	131	78
(Mon)	N64B	6	102	+10	42	0·18	0·11	0·98	39·0	139	76
(Mon)	K74	16	102	+10	44	0	0·15	1·00	29·4	134	74
1917 I	C	—	106	+06	40	0·04	0·19	0·99	32·7	121	88
60·12·9	N64B	4	96	+15	42	0·05	0·20	0·99	18·7	131	77
61·12·2	N64B	4	95	+15	42	0·09	0·11	0·99	22·6	135	74

* References and notes: S, present survey; W54, Whipple (1954); WH59, Whipple and Hawkins (1959); SH63, Southworth and Hawkins (1963); N64B, Nilsson (1964*b*); K74, component A from Kresáková (1974); C, comet Mellish 1917 I.

Table 12. Association 12·02 and μ-Geminids

Ident.	Ref.*	N	α	δ	V_∞	$1/a$	q	e	i	ω	Ω
12·02	S	6	95	+18	32	0·37	0·33	0·85	7·1	117	82
(μ-Gem)	S73	49	96	+23	29	0·68	0·27	0·82	0	129	76

* References: S, present survey; S73, Sekanina (1973*a*).

Southern Taurids and ζ-Perseids

The $D(A, B) \leqslant 0 \cdot 10$ stream search detected an association of 55 meteors consisting of 49 Southern Taurids and six ζ-Perseids. Tables 13 and 14 compare the respective components of this association with other observations. It should be noted that the mean orbits of the ζ-Perseids for the data of Nilsson (1964*b*) and Kashcheev and Lebedinets (1967) are for observations over May and June, whereas the observations for the present survey are limited to June. The longitude of perihelion for this stream is observed to increase during the period of observation, hence the higher value for the present survey.

Table 13. Radiant and orbit of Southern Taurids

Ident.	Ref.*	N	α	δ	V_∞	$1/a$	q	e	i	Ω	π
D·01	S	49	44	+11	31	0·58	0·30	0·82	7·1	24	153
(S. Tau)	W54	8	53	+14	30	0·43	0·38	0·84	5·5	43	155
(S. Tau)	MP61	17	43	+11	29	0·53	0·37	0·80	5·3	31	145
(S. Tau)	JW61	13	38	+10	30	0·55	0·34	0·81	5·1	25	142
(S. Tau)	SH63	11	28	+08	30	0·56	0·32	0·82	5·0	14	136
(S. Tau)	N64B	17	59	+17	26	0·48	0·50	0·76	4·2	56	155
(S. Tau)	BF66	61	62	+18	27	0·55	0·41	0·76	2·9	54	165
(S. Tau)	KL67	73	27	+09	31	0·48	0·33	0·84	2·2	15	133

* References: S, present survey; W54, Whipple (1954); MP61, McCrosky and Posen (1961); JW61, Jacchia and Whipple (1961); SH63, Southworth and Hawkins (1963); N64B, Nilsson (1964*b*); BF66, Baker and Forti (1966); KL67, Kashcheev and Lebedinets (1967).

Table 14. Radiant and orbit of ζ-Perseids

Ident.	Ref.*	N	α	δ	V_∞	$1/a$	q	e	i	☊	π
D.01	S	6	65	+27	30	0·58	0·30	0·82	7·1	81	150
(ζ-Per)	N64B	27	51	+22	30	0·59	0·31	0·82	4·8	71	127
(ζ-Per)	BF66	57	55	+21	29	0·55	0·33	0·81	3·2	73	132
(ζ-Per)	KL67	60	52	+23	30	0·62	0·31	0·80	5·7	71	128

* References: S, present survey; N64B, Nilsson (1964*b*); BF66, Baker and Forti (1966); KL67, Kashcheev and Lebedinets (1967).

Table 15. Association 10·11 and the Andromedids

Ident.	Ref.*	N	α	δ	V_∞	$1/a$	q	e	i	☊	π
10·11	S	2	23	+09	22	0·63	0·60	0·62	0·1	24	116
(And)	HSS59	23	—	—	—	0·29	0·75	0·78	6·3	224	106
(And)	SH63	14	19	+05	22	0·43	0·71	0·70	0·4	26	100
1852 III	C	—	23	+29	19	0·28	0·86	0·76	12·6	246	109

* References and notes: S, present survey; HSS59, Andromedid data of Hawkins *et al.* (1959); SH63, Andromedid data of Southworth and Hawkins (1963); C, comet Biela 1852 III.

Andromedid (Bielid) Stream

Association 10·11 of two meteors appears to belong to the formerly spectacular Andromedid stream associated with comet Biela 1852 III. Table 15 compares the orbital elements of this association with observations of photographic Andromedids by Hawkins *et al.* (1959) and Southworth and Hawkins (1963). Mean radiant data for the observations of Hawkins *et al.* are not given, but the individual radiant coordinates cover a broad area which is in general correspondence to the other radiant data presented, including those of Hasegawa (1962), for the theoretical stream radiant associated with the comet orbit.

Agreement in inclination and longitude of perihelion of our results with the photographic observations is quite good. The present association has a mean orbit which is considerably smaller than those of the other observations listed, as well as that of the comet. This might possibly indicate that the observed radio meteors belong to an older branch of the stream at a more advanced stage of evolution.

Table 16. Associations in Canis Minor and Hydra

Ident.	Ref.*	N	α	δ	V_∞	$1/a$	q	e	i	ω	☊
26·1	N62	3	127	+06	69	0·23	0·95	0·78	156	334	32
26·2	N62	3	116	+02	64	0·50	0·97	0·52	148	13	32
26·3	N62	3	120	+01	67	0·15	0·98	0·84	148	10	35
10·16	S	2	117	−05	66	0·17	0·97	0·82	136	341	25
10·17	S	2	121	+05	67	0·35	0·93	0·67	152	325	24
10·18	S	2	114	+06	67	0·39	1·00	0·61	153	359	25

* References: N62, Nilsson (1962); S, present survey.

Minor Streams in Canis Minor, Hydra and Aquarius

Table 16 compares three associations found by Nilsson (1962) in Canis Minor and Hydra with three pairs of orbits observed in this vicinity by the present survey also during October. The agreement confirms the reality of this stream.

The minor radiant in Aquarius observed by Nilsson (1964*b*) during March was observed again in this survey. Nilsson (1962) noted activity in this radiant also during February, which he felt could correspond to the day-time appearance of a stream observed at night in July. Although Nilsson only observed two meteors in the July radiant these correspond closely to three from the list of photographic meteors published by McCrosky and Posen (1961), confirming the stream. While the present survey did not detect the activity from the radiant in Aquarius during February, an association of seven meteors from this radiant was observed in March. Table 17 compares the radiant and orbit data for these associations. The present data confirm both the March and February associations of Nilsson. There is some discrepancy in the longitude of the ascending nodes between the February–March day-time stream and the probable night-time appearance of this stream in July. However, as it is apparently a broad stream this may still be acceptable. The correspondence of the longitudes of perihelion is excellent.

Table 17. Minor radiant in Aquarius

Ident.	Ref.*	N	α	δ	V_∞	$1/a$	q	e	i	☊	π
3·01	S	7	338	−08	35	0·59	0·18	0·89	1·8	359	42
(Feb. 5·2)	N62	3	317	−11	33	0·32	0·32	0·90	6·2	329	34
(July)	NMP	5	307	−15	29	0·34	0·38	0·87	4	217	47
61·3·2	N64B	3	340	−08	32	0·47	0·30	0·86	2·5	354	53

* References and notes: S, present survey; N62, Nilsson (1962); NMP, combined data of Nilsson (1962) and McCrosky and Posen (1961), in which the value for ☊ might be that for ☋ instead, since the inclination is small; N64B, Nilsson (1964*b*).

Stream Radiants Possibly Associated with Comet Lexell 1770 I

Nilsson (1964*b*) listed three radiants for the period 13–16 June 1961 in Ophiuchius and Sagittarius which may be associated with comet Lexell 1770 I. Nilsson (1963) previously discussed the possible association of the December Scorpids with the same comet. Southworth and Hawkins (1963) discovered a stream radiant for five meteors over the period 21 May to 16 June, which they named the θ-Ophiuchids. Cook (1970) listed the radiant of the μ-Sagittariid stream detected by Lindblad (1971*b*) for four meteors and has noted the association of this stream with comet Lexell. Terenteva (1968) listed a family of six minor streams detected over the period 16 June to 16 August, for which orbital elements and computed values of Tisserand's criterion suggest an association with comet Lexell. McKinley (1961) and Ellyett and Roth (1955) also gave radiants for streams in this region but velocity measurements were not available.

Two June streams with radiants in this general vicinity were observed in the present survey. The double intersection stream D·02 has six members in June and one meteor (No. 18043) observed on 12 February. Table 18 compares the radiant and orbit data for these meteors and an association (2·01) of three meteors with an adjacent radiant also from February.

Table 18. Two associations and double intersection stream

Ident.	N	α	δ	V_∞	$1/a$	q	e	i	☊	π
6·01	4	262	−25	26	0·43	0·52	0·77	1	260	357
D·02	6	271	−24	28	0·60	0·41	0·75	1	261	15
18043	1	308	−21	31	0·68	0·28	0·81	−2	323	17
2·01	3	316	−21	31	0·48	0·36	0·82	−5	324	29

Table 19 compares the orbital elements of stream 6·01 with comet Lexell. The agreement in π is excellent, but the discrepancy in ☊ is considerable. On the other hand, since the inclination of the stream is so low, good agreement exists between the nodes of 6·01 and Nilsson's Scorpids if we reverse the nodes of 6·01 and consider the inclination as negative. Association 6·01 with four members corresponds quite closely to the mean orbit for the θ-Ophiuchids stream given by Cook *et al.* (1973).

Table 19. Stream 6·01 and comet Lexell 1770 I

Ident.	a	q	e	i	☊	π
1770 I	3·2	0·67	0·79	1·6	132	356
6·01	2·3	0·52	0·77	−1·3	80	357
(Sco)	2·6	0·52	0·80	2	74	338
(θ-Oph)	2·9	0·46	0·73	−4·2	82	3

While there is undoubtedly considerable activity in this general region, additional observations appear to be adding to the confusion rather than resolving it. The similarities between the orbits of Table 18 seem too pronounced to be coincidental. The longitudes of perihelion are perhaps the most reliable guide to common origin. The value of π for stream D·02 is approximately as far behind π for comet Lexell as Nilsson's Scorpids are in front. Were it not for D·02, the longitude of perihelion of association 2·01 would not have led to the consideration of its possible association with this comet.

Table 20. Association 2·01 and χ- and α-Capricornids

Ident.	Ref.*	a	q	e	i	☊	π
2·01	S	2·08	0·36	0·82	5	144	29
(χ-Cap)	S73A	1·68	0·36	0·79	7	144	27
(α-Cap)	C73A	2·53	0·59	0·77	7	127	36

* References: S, present survey; S73A, Sekanina (1973*a*); C73A, Cook (1973*a*).

Association 2·01 also has some orbital similarities to comet Honda–Mrkos–Pajdušáková and has been linked with it in Table 26 below. However, 2·01 lies close to the orbit of the α-Capricornids (Table 20) whose traditional association with the comet was rejected by Cook (1973*a*). Even better agreement exists between stream 2·01 and the χ-Capricornid radio meteor stream of Sekanina (1973*a*). For the χ-Capricornids and a complex of nearby streams, Sekanina suggested a possible association with the minor planet 1936 CA (Adonis).

Cook (1970) classified a number of meteor streams in terms of the discrete beginning height criteria of Ceplecha (1967, 1968) and ascribed to the μ-Sagittariids a classification of type A or lower. It is most unfortunate that Cook was unable to classify the four June θ-Ophiuchids in the list of Southworth and Hawkins (1963) for comparison, in view of their possible related origin.

Cook (1973*b*) tentatively classified the α-Capricornids as type C1 according to beginning height, further weakening any link there might have been with the μ-Sagittariids. Upon re-examination of the data, Cook *et al.* (1973) find they can no longer support the confirmation of the μ-Sagitarriids as a separate stream.

There is no doubt that a diffuse concentration of orbits exists in this general region. The present observations have done little to solve the problems outlined by Cook (1970) in connection with this stream complex. Certainly, however, these observations give further confirmation to the existence of the complex in addition to extending its observation to February.

(*b*) *Toroidal meteor streams*

During February intense activity was observed centred on R.A. 179°, Dec. $-83°$. Group 2·14 consists of 47 meteors associated at a D level of 0·2. Agreement between the elements of the orbits within this association is generally good, although the range of inclinations is far greater than that normally indicative of a stream, varying from 33·6° to 106·6°. The spread in longitude of perihelion is similarly large, although some of this spread may be attributed to the generally low values of eccentricity for the members of the association. Nevertheless, there is a sharp peak at the mean longitude value of 125°.

The size of this association is a result of the use of the serial form of the D-criterion and the choice of the limiting value as 0·20. A smaller value of D would cause the present association of 47 meteors to be broken into a number of smaller associations. In this case it is necessary to decide whether it is the overall distribution of the meteors which is important, or whether the smaller associations are individually important. If the limit is too large there is the possibility that the orbits of sporadic meteors may act as stepping stones to link one part of orbit space to almost any other, with rather meaningless consequences. Nevertheless, in view of the lack of similar large groups of associations in the data for other months, it seems reasonably safe to assume that the broad overall association of 47 meteors is meaningful in this case, particularly in view of the general similarities in perihelion distance and eccentricities. There is a general profusion of associations of orbits with low eccentricities and large perihelion distances with radiants at deep southern declinations during the period December to March, and relatively little activity in this region during June and October. The fact that the present association of 47 meteors has not chained with other associations such as 2·13 nearby, containing 9 members, gives support for its reality.

Fig. 2*a* shows the observed distribution in inclination for members of this association. It can be seen that the majority of meteors have inclinations between 30° and 80° with two distinct peaks near 55° and 75°, which suggests that the association is a combination of two broad and probably related streams. It is possible that, for a larger sample of orbits, this concentration could be resolved into a cluster of smaller streams. Two such clusters have been noted by Sekanina (1973*a*) for Northern

Hemisphere radio meteors, both of which exhibit similarly large perihelion distances but generally lower values of inclination than for our association 2·14.

Fig. 2*b* shows the number of meteors of association 2·14 recorded for each day of observation during February. The equipment was operated for a few hours only on the 10 and 17 February, and continuously for the days in between. There is some indication of a slow rise in the meteor rate to a broad peak over the period 13–15 February, although it is not possible to say for certain when and how suddenly the rate drops after this point.

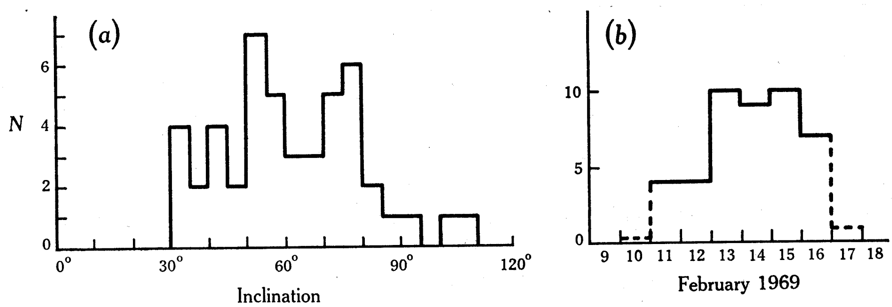

Fig. 2. Distributions for the association 2·14 of toroidal orbits with: (*a*) inclination and (*b*) dates of detection.

It is interesting to note the relative lack of meteor associations of this kind amongst the data of Nilsson (1964*b*) whose is the only available survey of individual meteor orbits covering the same range of declinations with which comparisons of the present data may be made. The Puppid shower observed by Nilsson and previously by Ellyett and Roth (1955) and Weiss (1957, 1960) is an example of such a meteor stream. This shower probably is related to associations 12·06, 12·07 and 12·08 in the present survey (Table 21). Association 12·06 agrees with Nilsson's elements for this stream well in *e* and π but not in *i*, whereas the two associations 12·07 and 12·08 are closer to the inclination of 70° but have exceptionally low eccentricities, so that perihelion longitude is no longer a reliable guide.

Table 21. Three Puppid/Velid associations

Ident.	Ref.*	N	α	δ	V_∞	$1/a$	q	e	i	ω	Ω
60·12·8	N64B	5	138	−53	41	0·48	0·98	0·53	70	353	78
61·12·6	N64B	3	143	−54	40	0·53	0·98	0·48	70	340	77
12·06	S	7	135	−63	35	0·44	0·97	0·56	57	344	82
12·07	S	6	141	−43	37	0·84	0·98	0·16	70	0	81
12·08	S	3	145	−45	39	0·94	0·98	0·08	75	1	82

* References: N64B, Nilsson (1964*b*); S, present survey.

Association 1·01 (Table 22) corresponds well to an association of three meteors with a radiant in Carina detected by Nilsson (1962). The Carina radiant was also observed to be active in December by Nilsson (1964*b*) and in February in the present survey. Details of the streams associated with these radiants are given in Table 23. Both of these associations have orbital similarities to the Puppids and Carinids, differing most markedly in perihelion longitude. Until more data are gathered concerning all of these associations we can do little more than note their similarities, but it seems reasonable to refer to them as a 'family' of streams.

Table 22. Association 1·01 and Carina radiant

Ident.	Ref.*	N	α	δ	V_∞	$1/a$	q	e	i	ω	Ω
	N62	3	156	−65	40	0·42	0·98	0·59	70	0	119
1·01	S	3	160	−63	43	0·34	0·98	0·64	74	7	122

* References: N62, Nilsson (1962); S, present survey.

Nilsson (1964*b*) found only two meteor showers with orbits of eccentricity less than 0·6, the Puppids with eccentricity of 0·53 to 0·48 and the Carinids with eccentricity 0·59. From this observation he deduced that the short-period highly inclined orbits of low eccentricity which appear to become more prominent with smaller magnitudes (Hawkins 1962) do not contribute to the total distribution as showers, but rather as meteors in individual and separate orbits. It is probably due to the ability of the present survey to resolve meteors of limiting magnitude +8 compared with Nilsson's limiting magnitude of +6 that the present results lead us to the reverse conclusion.

Table 23. Streams associated with Carina radiants

Ident.	Ref.*	N	α	δ	V_∞	$1/a$	q	e	i	ω	Ω
60·12·7	N64B	4	155	−61	40	0·34	0·91	0·69	67	324	76
2·13	S	9	152	−65	37	0·42	0·93	0·60	62	33	145

* References: N, Nilsson (1964*b*); S, present survey.

Although velocity selection effects favour the observation of short-period low eccentricity streams with high inclination rather than low inclination, the relative dearth of highly retrograde orbits of similar shape in the observations suggests that the predominance of this type of orbit at high inclinations is not merely a result of observational selection. It is also worth noting that the astronomical collision probabilities work strongly against the detection of streams of this type, as the Earth tends to pass through them more nearly normally rather than along the stream axis, and hence in the shortest time possible. Fig. 3 compares the distribution in inclination of associated meteors for various ranges of eccentricity. The reality of the toroidal group is clearly apparent.

Kashcheev and Lebedinets (1967) recorded 11 associations of high inclination and low eccentricity, of which seven have values of $q > 0\cdot87$ a.u. A number of the radiants for these associations are visible from Adelaide. Table 24 compares associations 10·06, 10·17 and 10·18 from this survey with association 40 of Kashcheev and Lebedinets. The former comprise three of the four low eccentricity associations observed during October, all of which have positive declinations. Association 40 is the only association of low eccentricity meteors observed by Kashcheev and Lebedinets during October.

The agreement between the two sets of data is sufficiently close to suggest that they are observations of the one stream. This stream has not been observed photographically or with less sensitive radar equipments, and this could indicate that the low value of eccentricity may be a result of prolonged action of the Poynting–Robertson effect which has reduced the orbit size for the smaller members of a meteor stream originally reaching perihelion at a distance exceeding 1 a.u.

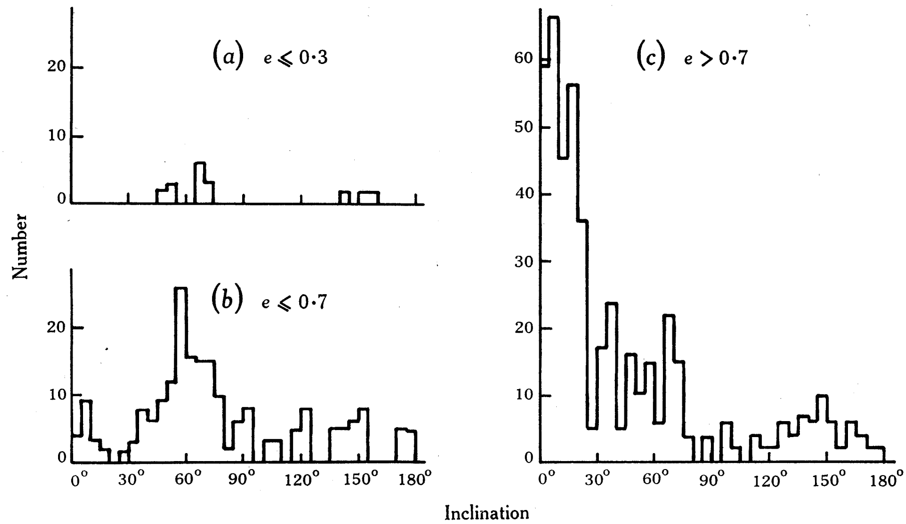

Fig. 3. Distribution of all associated meteor orbits with inclination for the indicated ranges of eccentricity.

This survey has recorded a number of February streams besides those of high inclination already discussed. Of these, association 2·18 shown in Table 25 appears sufficiently significant to suggest that the reason it has not been detected previously may also be because it is constituted entirely of small particles. The lack of published observations of streams during this month is noteworthy, notwithstanding the fact that the majority of the toroidal streams detected in February have extremely southern radiants.

Table 24. Three October associations

Ident.	Ref.*	N	α	δ	V_∞	$1/a$	e	q	i	ω	Ω
40	KL67	21	108	+15	66	0·53	0·51	0·94	166	3	23
10·06	S	3	115	+17	68	0·41	0·58	0·99	172	352	23
10·17	S	2	121	+05	67	0·35	0·67	0·93	152	325	24
10·18	S	2	114	+06	67	0·39	0·61	1·00	153	359	25

* References: KL67, Kashcheev and Lebedinets (1967); S, present survey.

(c) *Search for cometary associations with Southern Hemisphere meteor streams*

Hasegawa (1962) predicted stream radiants for comets in the Baldet and De Obaldia catalogue (1952) which pass within 0·2 a.u. of the Earth's orbit. A search for comets associated with the streams of the present survey has been conducted by comparison first with Hasegawa's radiant data, and subsequent comparison of the orbital elements of promising associations with those for the appropriate comets given by Baldet and De Obaldia.

The present search constitutes the first comprehensive search for cometary associations in the Southern Hemisphere, although Nilsson (1964*b*) compared his survey data with the list of 19 meteor radiants for comets given by Porter (1952) and reported the association with comet Lexell 1770 I discussed earlier. Particular attention has been given to the streams of high inclination and low eccentricity, and a number of associations have been found with long-period comets. Differences in ☊ may be expected to occur where the stream orbit is contracted markedly by the Poynting–Robertson effect. For a direct orbit, such a contraction should cause ☊ to increase if perihelion occurs south of the ecliptic plane. In several cases, agreement is good in most elements though not in the alignment of the line of apsides. For others, only the inclinations differ significantly. Where the generating comet is of long period or parabolic and the stream of short period, some small differences may arise through the differential action of perturbing forces, although such differences will rarely be sufficient to explain the discrepancies.

Table 25. Association 2·18

Ident.	N	α	δ	V_∞	$1/a$	q	e	i	ω	☊
2·18	11	346	−24	18	0·44	0·82	0·62	2·1	299	144

Larger differences may be countenanced by considering that the particles have been ejected with substantial velocities relative to the comet some time prior to perihelion. This mechanism can produce variations in all of the orbital elements, including inclination and argument of perihelion, but should have least effect upon ☊ if the stream is generated near 1 a.u. from the Sun. Southworth (1963) has determined that the Perseid orbits suggest an explosive origin for this stream at 1·5 a.u. from the Sun and 1·3 a.u. north of the ecliptic plane at approximately 1000 years ago. It is possible that such explosive origins for meteor streams are the rule rather than the exception, although with considerable variation in degree.

The association of comet Mellish 1917 I with the Monocerotids has already been noted, as has that of comet Lexell 1770 I with the Scorpid/Ophiuchid complex.

Table 26 lists 17 comets and associations from the present survey which may be related. In several instances the agreement is so good that no doubt arises. In others the doubt cannot be eliminated although the similarities are pronounced. Nevertheless, as noted by Kashcheev and Lebedinets (1967) 'if the comet's orbit passes at a large distance from the Earth's orbit, the orbit of the related stream, to be observed at the Earth, should differ noticeably from the comet's orbit.'

For this reason, rather than being over-cautious, all reasonable associations have been listed in the hope that some of these may stimulate further investigation. In three instances, two comets are listed as possibly being associated with the one group of streams, although in each case the agreement is generally better with one comet than the other. Possibly the streams are associated with neither of the listed comets, but with a third; or possibly the streams are the remnants of a comet which belonged to a comet group containing the other two.

Among the probable cometary associations listed in Table 26 there are a number between long-period comets and high inclination streams which deserve special note. The agreement in ☊ for associations 2·15, 2·39 and 2·42 with comet Schwassmann–

Wachmann–Peltier 1930 I is particularly close. In view of the close proximity of the inclination in each case to 90°, the agreement in this element must be good if the association is to be regarded as valid.

Associations 12·06, 12·07 and 12·08 correspond to the Puppid/Velid complex already discussed. In this case, the association of the complex with comet Thiele 1906 VII is more likely than with comet Johnson 1935 I because of the agreement in ☊. Probably, more importantly, the similarities in q between the meteor associations imply that the streams may have contracted under the Poynting–Robertson effect from the cometary orbit with larger q rather than having increased in q from the smaller value.

The possible link between association 2·01 and comet Honda–Mrkos–Pajdušáková has already been questioned above in the light of the re-appraisal by Cook (1973*a*) of the association of this comet with the α-Capricornids. Nevertheless, Marsden and Sekanina (1971) have confirmed the existence of a strong nongravitational force influencing the comet's motion, and the possibility of related meteor streams with significantly different orbits should not be ruled out, for reasons discussed below.

Although association 2·24 contains two meteors only, some confirmation of its reality is given by the similarity of the orbit to that of comet Helfenzrieder 1766 II. Further confirmation is given by Terenteva (1967) who described a family of minor streams possibly associated with this comet including two, the η-Leonids and the 40 Leo Minorids, to which the present association 2·24 is intermediate.

The association between 3·04, 3·05 and comet Pons–Bouvard–Olbers 1804 is particularly interesting. Both 3·04 and 3·05 are undoubtedly significant with 10 and 11 members respectively. Association 3·04 is a good example of a 'toroidal' meteor stream and yet there is no doubt that it is related to 3·05, which certainly is not. The association with comet 1804 is also unmistakable, and yet this comet is parabolic. It should be noted that the value of a given for 3·05 is only approximate. The actual range of a for this group varies from 4·17 a.u. through to one slightly hyperbolic orbit. There is possibly a case for further subdivision of this group into two groups, since five of the orbits have $4\cdot17 \leqslant a \leqslant 6\cdot67$ a.u., while for the remainder $a \geqslant 10\cdot1$ a.u.

Despite their strengths neither association 3·05 nor 3·04 was detected by Nilsson (1964*b*) during 1961, possibly because his recording period during March ended on the 17th, approximately when the March recording period for the present survey began. Although too far south for observation from the Northern Hemisphere, the radiants of these streams are continuously observable at Adelaide. It would be interesting to determine whether any photographic meteor activity is associated with 3·05, and if so, whether 3·04 is also detectable visually or photographically.

(*d*) *Low eccentricity stream formation*

The appearance of the toroidal class of meteors at only faint radio magnitudes points towards its origin in the differential action of the Poynting–Robertson effect upon small meteors in streams. The similarities of 3·04, 3·05 and comet Pons–Bouvard–Olbers 1804 give further evidence that the low eccentricity orbits could be the result of evolution rather than direct formation from low eccentricity comets. Yet there is one major problem common to several of the cometary associations listed, which at present must remain unsolved. Approximate calculations show that, for a 'typical' low density faint radio meteor in a circular orbit near 1 a.u. from the Sun, the Poynting–Robertson effect alone will cause the meteoriod to take $\sim 10^6$ years to drift into the Sun. Yet if comet 1804 is responsible for stream 3·04 then, since it is parabolic, only 170 years have been available for 3·04 to contract from $a > 10$ a.u. to the present value of 2·13 a.u. For association 2·16 and comet Bečvár 1947 III, only 22 years have been available for a similar contraction to take place.

Table 26. Probable cometary associations

Ident.*	a	q	e	i	ω	Ω	π	α	δ	V_∞	N
1947 III	—	0·96	1	129·2	182	322	144	237	+11	66	
2·16	2·3	0·98	0·56	118·0	171	323	134	241	+15	59	5
574	—	0·96	1	46·5	15	128	143	111	−61	31	
2·11	3·0	0·98	0·67	48·4	354	145	139	99	−76	31	5
2·10	9·4	0·98	0·89	47·2	12	145	157	110	−65	32	3
2·30	10·9	0·97	0·91	47·8	14	144	158	112	−64	33	2
1905 III	37·1	1·11	0·96	40·2	358	157	155	86	−62	27	
1766 II	2·5	0·40	0·85	8·0	178	76	254	157	+09	27	
2·24	2·1	0·46	0·78	5·3	283	323	245	154	+17	27	2
1954 III	3·1	0·56	0·82	13·2	184	233	57	324	−14	25	
2·01	2·1	0·36	0·82	4·5	246	144	29	316	−21	31	3
2·19	1·4	0·51	0·63	1·7	75	324	38	318	−14	23	2
2·21	1·8	0·67	0·62	5·1	99	323	61	326	−04	21	2
1930 I	3151	1·09	1·00	99·9	325	148	113	249	−68	55	
2·15	13·2	0·95	0·93	70·2	330	144	114	250	−86	44	4
2·39	2·0	0·85	0·57	87·1	307	146	92	247	−71	48	2
2·42	50	0·79	1·00	101·6	307	145	92	256	−64	57	2
1885 III	42·2	0·75	0·98	59·1	43	205	248	185	−75	38	
3·06	1·6	0·88	0·41	65·7	57	177	234	195	−74	37	5
3·07	2·0	0·65	0·65	57·3	83	179	262	184	−58	36	3
3·09	20·6	0·76	0·90	59·3	58	178	236	173	−60	40	3
1834	—	0·51	1	6·0	50	227	277	190	−04	29	
3·17	3·2	0·41	0·86	1·2	105	177	282	183	−03	30	2
3·21	2·3	0·46	0·80	11·5	103	179	282	181	−14	28	2
3·22	2·0	0·32	0·84	13·9	300	358	298	197	+04	31	2
3·23	1·6	0·31	0·81	18·7	122	180	303	191	−21	31	2
3·27	16·2	0·32	1·04	26·0	109	178	287	184	−19	40	2
1930 VII	—	0·41	1	4·2	63	229	292	195	−07	32	
1938	4·9	1·18	0·76	11·7	209	67	276	214	+22	14	
6·02	3·1	0·93	0·68	14·0	216	79	295	234	+20	18	3
1618 II	—	0·39	1	37·2	287	76	3	276	00	39	
6·09	1·9	0·15	0·90	39·5	324	80	44	289	−06	38	13
6·10	2·6	0·37	0·86	43·3	292	79	11	280	+06	37	4
6·11	0·9	0·14	0·84	66·3	333	80	53	303	+03	37	5
1874 II	—	0·89	1	148·4	332	274	246	20	−11	69	
6·41	3·3	0·78	0·76	157·6	297	262	199	12	−07	66	2

Table 26 (*Continued*)

Ident.*	a	q	e	i	ω	Ω	π	α	δ	V_∞	N
1723	—	1·00	1	130·0	331	14	346	115	−08	66	
10·06	2·4	0·99	0·58	171·6	352	23	15	115	+17	68	3
10·16	5·9	0·97	0·82	135·7	341	25	6	117	−05	66	2
10·17	2·8	0·93	0·67	151·6	325	24	349	121	+05	67	2
10·18	2·6	1·00	0·61	153·0	359	25	24	114	+06	67	2
1888 III	9796	0·90	1·00	74·2	59	101	161	130	−35	45	
1·1	3·0	0·98	0·64	74·3	7	122	129	160	−63	43	3
1906 VII	69·8	1·21	0·98	56·3	9	85	93	110	−59	37	
12·06	2·3	0·97	0·56	57·3	344	82	66	135	−63	35	7
12·07	1·2	0·98	0·16	69·5	0	81	81	141	−43	37	6
12·08	1·1	0·98	0·08	74·5	1	82	83	145	−45	39	3
1935 I	93·2	0·81	0·99	65·4	18	91	109	120	−53	40	
1804	—	1·07	1	56·5	332	177	149	63	−52	36	
3·05	10·0	0·98	0·87	58·3	346	178	164	50	−78	38	10
3·04	2·1	0·98	0·53	55·3	347	178	165	51	−81	34	11

* Identifications for comets: 1947 III, Bečvár; 574, (China); 1905 III, Giacobini; 1766 II, Helfenzrieder; 1954 III, Honda–Mrkos–Pajdušáková; 1930 I, Schwassmann–Wachmann–Peltier; 1885 III, Brooks; 1834, Gambart–Dunlop; 1930 VII, Nakamura; 1938, Gale; 1618 II, (Rome); 1874 II, Winnecke–Borelly–Tempel; 1723, Sanderson; 1888 III, Brooks; 1906 VII, Thiele; (associations 12·06, 12·07 and 12·08 are the Puppid/Velid complex); 1935 I, Johnson; 1804, Pons–Bouvard–Olbers.

There are two possible explanations of the apparent time-scale discrepancy:

(i) We may need to study the mechanics of ejection of particles from comets in much greater depth. Long-period comets do not show the preference for the ecliptic plane exhibited by most other members of the solar system, so that the relation of their origin to that of the other bodies is not clear. If we suppose, despite this, that the majority of long-period comet nuclei rotate in the direct sense, irrespective of whether their orbital motion is direct or retrograde, then there will be two major consequences: Solar heating on the sunward side of a comet near perihelion in a direct orbit will result in the ejection of material with a velocity component towards the antapex of the comet's way and into an orbit of lower eccentricity. For a directly rotating comet in a retrograde orbit, the ejection of material will be displaced towards the cometary apex. For a long-period or parabolic comet, such a displacement could result in the meteors created having hyperbolic orbits in a large number of cases. This model could thus explain at once the dearth of retrograde meteors and the observed tendency for meteor stream orbits to have lower eccentricities than the associated comets. The model is not suggested to be the sole cause of the low eccentricity orbits of the toroidal group; the lack of meteors of photographic size amongst the toroidal group seems to indicate that a mass-dependent process has also contributed.

(ii) A second explanation of the apparent time-scale discrepancies, not mutually exclusive but rather complementary to the comet rotation hypothesis, is that long-period comets may frequently occur in comet groups. Such groups may possibly have been generated by the disintegration of giant comets at some long-past perihelion passage. If this were so then it would be possible that the low eccentricity streams observed to be associated with recent comets may actually be derived from previous members of a comet group.

Rotational motion of comet nuclei is an idea originally considered by Whipple (1950). Observations of cometary motion for a number of short-period comets confirm the action of nongravitational forces generally acting strongly away from the Sun with a smaller transverse component in the orbit plane. This is apparently the result of reaction to ejection of gas and/or solid material from the comet, since the degree of the nongravitational behaviour of the comet tends to decrease with time and is not apparent at all for comets of asteroidal appearance (Marsden 1969).

Marsden (1968, 1969, 1970) has studied the effect of nongravitational forces on a number of comets. For the short-period comets the distribution of the nongravitational forces suggests generally small rotations, with direct and retrograde sense being about equally probable. The long-period comets Burnham 1960 II and Arend–Roland 1957 III were observed to be accelerating slightly, implying retrograde spin since both comets have retrograde orbits. Marsden's calculations, which show the transverse component of the nongravitational force acting on a comet to lie in the orbital plane, are all for comets with orbits close to the ecliptic plane. It remains to be seen whether this still applies to orbits of high inclination. A possible explanation of the observed erratic motion of some comets in terms of collisions with hypothetical interplanetary boulders has been critically examined by Marsden and Sekanina (1971) and Sekanina (1973*b*) and found to be worthy of further investigation.

Some interesting problems arise when trying to reconcile the present arguments with the findings of Dohnanyi (1970). While these observations give support to Dohnanyi's conclusion that sporadic meteors may be derived from shower meteors and hence from comets, they also indicate at first sight that some form of radiation damping may have resulted in the streams of low eccentricity observed, whereas according to Dohnanyi collisional processes should have predominated to destroy the stream. On the other hand, as Dohnanyi recognized, collisional processes will have the highest probability of occurrence near stream perihelion when the space density of particles within the stream is greatest. Collisions at perihelion could thus result in the creation of lower eccentricity orbits associated with the main stream, in addition to higher eccentricity orbits to balance the conservation laws. The higher eccentricity orbits could in a number of cases be hyperbolic, and thus have a low probability of detection. Such a collision mechanism seems to be the most likely explanation of the definitely hyperbolic orbits observed in the Orionids of the present survey (3·1·4). The low eccentricity orbits would be more apparent at fainter magnitudes, since the distribution of particle sizes amongst collision products should include relatively more smaller particles than the primary cometary ejecta.

It is also apparent that the greatest space density of particles must occur within the comet itself and in its immediate environs, so that collision probabilities may be many orders of magnitude higher at this stage in the life of a stream than subsequently. Consideration should be given to the likelihood of low eccentricity orbits being directly created by collision during stream formation, and to the likely relative mass distributions to be encountered in such orbits. Such a process would not only be consistent with Dohnanyi's (1970) model of stream dispersal but could remove the apparent discrepancy in time scales noted already in regard to the action of the Poynting–Robertson effect in the creation of low eccentricity streams.

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Appendix

Table A1. Associations of two orbits

Ident.	Mean date	No.	$1/a$ (a.u.$^{-1}$)	q (a.u.)	e	i °	ω °	☊ °	α °	δ °	V_∞ (km s^{-1})	$\bar{D}$(M, N)
12·10	12	2	0·65	0·12	0·92	9·4	146	80	108	+19	38	0·03
12·11	11	2	0·52	0·15	0·92	8·0	141	80	104	+19	37	0·02
12·12	12	2	0·41	0·89	0·63	19·4	318	80	294	−70	20	0·07
12·13	13	2	0·85	0·23	0·80	17·6	44	261	237	−08	31	0·09
12·14	12	2	0·54	0·95	0·47	29·0	333	81	84	−84	21	0·09
12·15	11	2	0·52	0·14	0·93	30·9	322	259	109	+34	40	0·04
12·16	13	2	0·60	0·11	0·93	38·2	33	261	232	−06	40	0·06
12·17	12	2	0·48	0·79	0·62	38·6	299	80	212	−74	28	0·04
12·18	15	2	0·35	0·45	0·84	75·9	260	83	203	−50	46	0·05
12·19	14	2	−0·17	0·36	1·09	110·3	102	82	126	−06	60	0·05
12·20	13	2	0·82	0·44	0·64	122·4	65	261	204	+16	54	0·10
12·21	14	2	0·02	0·99	0·98	169·3	6	83	169	−02	73	0·08
12·22	13	2	0·09	0·86	0·92	149·4	137	260	190	+14	69	0·06
1·02	22	2	0·36	0·19	0·93	8·8	133	122	143	+10	38	0·05
1·03	21	2	0·24	0·96	0·77	30·4	340	121	37	−68	24	0·06
1·04	22	2	0·43	0·98	0·57	50·9	358	122	123	−71	32	0·05
1·05	22	2	0·35	0·59	0·79	145·4	264	302	195	+11	64	0·07
1·06	21	2	0·59	0·37	0·78	155·4	296	301	188	+07	60	0·05
2·19	13	2	0·72	0·51	0·63	1·7	75	324	318	−14	23	0·05
2·20	12	2	0·61	0·08	0·95	0·9	27	323	296	−21	40	0·03
2·21	11	2	0·56	0·67	0·62	5·1	99	323	326	−04	21	0·04
2·22	15	2	0·71	0·09	0·93	4·0	331	327	177	+03	37	0·04
2·23	15	2	0·60	0·37	0·78	5·3	296	326	162	+13	28	0·04
2·24	12	2	0·48	0·46	0·78	5·3	283	323	154	+17	27	0·03
2·25	14	2	1·17	0·03	0·97	15·0	348	325	188	00	37	0·04
2·26	15	2	1·13	0·25	0·72	12·6	323	327	181	+12	25	0·05
2·27	13	2	0·25	0·25	0·93	18·1	123	144	158	−02	37	0·04
2·28	14	2	0·63	0·10	0·93	23·8	330	324	178	+10	38	0·05
2·29	12	2	0·73	0·84	0·39	44·2	297	143	339	−81	28	0·08
2·30	13	2	0·09	0·97	0·91	47·8	14	144	112	−64	33	0·03
2·31	14	2	0·65	0·15	0·90	48·4	322	325	186	+18	40	0·08
2·32	15	2	0·10	0·52	0·97	53·8	87	146	153	−31	41	0·10
2·33	15	2	0·63	0·70	0·56	61·1	79	146	161	−50	37	0·10
2·34	12	2	0·70	0·79	0·45	63·7	290	143	272	−79	37	0·05
2·35	11	2	0·45	0·98	0·55	65·5	4	143	161	−74	39	0·08
2·36	16	2	0·21	0·98	0·78	73·6	13	147	170	−72	44	0·07
2·37	12	2	−0·23	0·94	1·24	76·0	337	144	224	−85	49	0·09
2·38	14	2	0·70	0·98	0·31	76·3	11	145	191	−70	41	0·04
2·39	15	2	0·50	0·85	0·57	87·1	307	146	247	−71	48	0·09

Table A1 (*Continued*)

Ident.	Mean date	No.	1/a (a.u.⁻¹)	q (a.u.)	e	i °	ω °	☊ °	α °	δ °	V_∞ (km s⁻¹)	$\bar{D}$(M, N)
2·40	15	2	0·06	0·97	0·92	86·6	345	147	215	−75	51	0·05
2·41	12	2	0·19	0·94	0·82	96·8	332	143	227	−67	54	0·04
2·42	14	2	0·02	0·79	1·00	101·6	307	145	256	−64	57	0·06
2·43	15	2	0·40	0·97	0·61	105·0	344	146	223	−61	55	0·09
2·44	14	2	0·49	0·94	0·53	104·1	210	324	235	+24	54	0·07
2·45	15	2	0·20	0·87	0·81	114·7	43	146	202	−48	60	0·10
2·46	12	2	0·46	0·22	0·90	119·9	311	323	201	+11	54	0·06
2·47	13	2	0·40	0·51	0·79	131·8	265	144	258	−44	60	0·08
2·48	13	2	0·43	0·42	0·81	138·8	288	324	210	+06	60	0·09
2·49	13	2	0·60	0·92	0·48	145·4	39	144	218	−35	64	0·06
2·50	14	2	0·32	0·64	0·77	152·8	260	324	217	−01	65	0·09
2·51	14	2	0·56	0·96	0·46	153·4	205	325	232	−04	65	0·04
2·52	16	2	0·19	0·97	0·82	155·6	165	327	242	−07	70	0·07
2·53	10	2	0·43	0·05	0·98	174·7	202	141	273	−24	54	0·05
2·54	14	2	0·44	0·96	0·58	178·8	159	145	236	−20	68	0·00
3·17	17	2	0·32	0·41	0·86	1·2	105	177	183	−03	30	0·03
3·18	19	2	0·40	0·10	0·96	8·0	148	178	202	−12	40	0·05
3·19	19	2	0·16	0·76	0·88	10·3	61	178	157	−10	23	0·04
3·20	18	2	0·27	0·56	0·85	10·7	88	177	172	−11	27	0·03
3·21	20	2	0·43	0·46	0·80	11·5	103	179	181	−14	28	0·03
3·22	19	2	0·50	0·32	0·84	13·9	300	350	197	+04	31	0·04
3·23	21	2	0·62	0·31	0·81	18·7	122	188	191	−21	31	0·03
3·24	19	2	0·44	0·29	0·86	23·8	302	358	201	+09	34	0·05
3·25	18	2	1·04	0·06	0·94	21·4	162	178	211	−19	37	0·09
3·26	17	2	0·27	0·33	0·91	24·6	66	357	337	+08	36	0·05
3·27	19	2	0·06	0·32	1·04	26·0	109	178	184	−19	40	0·09
3·28	18	2	0·89	0·34	0·70	37·8	308	357	215	+17	30	0·07
3·29	21	2	0·30	0·98	0·70	39·8	17	180	114	−65	27	0·05
3·30	19	2	0·15	0·63	0·88	52·5	282	178	0	−50	38	0·10
3·31	18	2	−0·40	0·20	1·08	49·9	58	357	330	+07	49	0·03
3·32	20	2	0·56	0·24	0·87	39·5	27	0	329	+13	36	0·05
3·33	18	2	0·87	0·87	0·25	49·4	291	179	3	−75	29	0·05
3·34	21	2	0·73	0·13	0·89	51·8	211	177	330	−32	39	0·08
3·35	19	2	0·40	0·13	0·93	54·0	324	0	216	+04	42	0·09
3·36	18	2	0·28	0·85	0·75	65·8	48	178	180	−69	40	0·08
3·37	19	2	0·49	0·99	0·51	68·4	349	178	324	−86	39	0·04
3·38	18	2	0·49	0·08	0·94	67·7	26	358	318	−01	44	0·08
3·39	18	2	0·31	0·83	0·74	73·4	307	178	341	−69	44	0·07
3·40	18	2	0·35	0·93	0·68	76·0	328	177	328	−77	44	0·04
3·41	18	2	−0·03	0·98	1·03	88·8	2	178	263	−79	53	0·08
3·42	18	2	0·79	0·34	0·73	128·3	125	178	232	−39	54	0·07
3·43	18	2	0·05	0·71	0·96	130·3	245	357	247	+04	64	0·07
3·44	19	2	0·67	0·99	0·33	138·8	348	177	270	−46	61	0·09
3·45	21	2	0·78	0·95	0·26	141·1	40	181	266	−44	60	0·07
3·46	19	2	0·32	0·85	0·72	145·4	49	179	253	−41	65	0·07
3·47	19	2	0·49	0·96	0·53	146·3	205	359	264	−05	64	0·09
3·48	17	2	0·91	0·83	0·24	154·4	279	176	274	−36	60	0·10
3·49	20	2	0·85	0·68	0·42	178·6	86	0	77	+22	61	0·08
3·50	20	2	0·42	0·74	0·69	177·4	292	179	285	−24	67	0·00
6·19	12	2	0·79	0·22	0·82	1·1	43	80	56	+21	31	0·04
6·20	12	2	0·56	0·06	0·96	12·7	336	81	292	−19	40	0·10
6·21	12	2	0·58	0·31	0·82	4·8	237	261	65	+18	30	0·05
6·22	11	2	0·46	0·26	0·88	5·8	127	260	278	−27	33	0·04
6·23	12	2	0·84	0·13	0·89	11·8	217	261	52	+13	34	0·03
6·24	10	2	0·56	0·07	0·96	13·1	205	259	48	+14	40	0·05
6·25	11	2	0·20	0·26	0·95	16·3	57	80	60	+30	37	0·05
6·26	12	2	0·72	0·02	0·99	18·6	191	261	43	+14	42	0·04
6·27	13	2	0·51	0·22	0·89	20·5	228	261	61	+09	35	0·05
6·28	13	2	0·98	0·18	0·82	20·4	215	261	53	+07	30	0·05
6·29	11	2	0·04	0·17	1·00	21·5	44	80	55	+28	43	0·05

Table A1 (*Continued*)

Ident.	Mean date	No.	$1/a$ (a.u.$^{-1}$)	q (a.u.)	e	i °	ω °	Ω °	α °	δ °	V_∞ (km s^{-1})	$\bar{D}$(M, N)
6·30	13	2	0·45	0·10	0·95	24·0	212	262	54	+11	40	0·02
6·31	13	2	0·28	0·12	0·97	28·4	322	82	287	−13	42	0·01
6·32	14	2	1·07	0·17	0·81	33·1	211	263	51	00	31	0·05
6·33	9	2	0·56	0·18	0·90	37·9	318	78	285	−06	38	0·04
6·34	11	2	0·92	0·10	0·90	61·6	153	259	307	−37	39	0·09
6·35	10	2	0·75	0·13	0·91	69·6	213	259	44	−04	42	0·04
6·36	12	2	0·29	0·42	0·85	123·6	286	81	314	+06	57	0·09
6·37	13	2	0·34	0·64	0·78	126·5	261	82	321	+12	59	0·04
6·38	11	2	0·26	0·92	0·76	128·1	321	260	14	−25	62	0·08
6·39	12	2	0·20	0·27	0·94	143·0	59	81	20	+22	59	0·09
6·40	11	2	0·74	0·48	0·64	145·1	290	80	326	+02	58	0·06
6·41	13	2	0·31	0·78	0·76	157·6	297	262	12	−07	66	0·04
6·42	9	2	1·05	0·69	0·27	158·0	301	78	338	+02	57	0·09
6·43	10	2	0·59	0·83	0·50	162·3	118	79	356	+08	64	0·08
6·44	8	2	0·30	0·71	0·79	167·3	108	78	3	+08	66	0·08
6·45	12	2	0·28	0·53	0·85	179·9	267	261	80	+23	28	0·00
6·46	10	2	0·40	0·71	0·64	173·3	257	79	334	−07	64	0·06
10·07	18	2	−0·05	0·68	1·04	132·9	67	24	90	00	66	0·06
10·09	19	2	−1·23	0·72	1·89	147·1	55	25	89	+06	78	0·10
10·10	19	2	−1·10	0·68	1·75	164·5	59	25	90	+15	79	0·08
10·11	16	2	0·63	0·60	0·62	0·1	92	24	23	+09	22	0·03
10·12	17	2	1·24	0·16	0·80	2·6	152	24	55	+18	28	0·02
10·13	16	2	0·06	0·59	0·94	5·5	81	23	20	+01	29	0·05
10·14	17	2	0·49	0·14	0·92	45·7	143	24	56	+03	41	0·05
10·15	17	2	0·64	0·04	0·98	48·8	162	23	58	+12	44	0·05
10·16	18	2	0·17	0·97	0·82	135·7	341	25	117	−05	66	0·06
10·17	18	2	0·35	0·93	0·67	151·6	325	24	121	+05	67	0·09
10·18	19	2	0·39	1·00	0·61	153·0	359	25	114	+06	67	0·07
						Double intersections						
D·06	6·10	1	0·82	0·44	0·63	1·9	65	78	64	+24	23	0·03
	10·16	1					118	23	35	+12	23	
D·07	6·12	1	0·53	0·59	0·68	3·7	269	261	80	+18	23	0·01
	12·12	1					269	261	80	+29	23	
D·08	2·10	1	0·53	0·31	0·83	3·4	119	141	156	+08	31	0·04
	10·17	1					58	204	189	−01	31	
D·09	6·12	1	0·58	0·65	0·62	154·4	259	81	330	+04	62	0·10
	12·16	1					269	84	187	−04	63	
D·10	6·12	1	0·96	0·94	0·09	152·3	166	81	347	+10	60	0·08
	12·16	1					131	84	167	−10	59	
D·11	6·14	1	0·61	0·62	0·60	104·7	97	263	343	−45	51	0·10
	12·13	1					95	261	209	+23	52	

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