ORBITS OF PHOTOGRAPHIC METEORS[1]

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One set of observational quantities that may be used to determine the six orbital elements of the heliocentric orbit of a body is its simultaneous position and velocity components. Most photographic observations of meteors, for whatever purpose they are made, contain within them the necessary ingredients to determine a (vector) velocity with respect to the earth. The components of this observed velocity due to gravity and the earth's diurnal and orbital motions are readily removed, giving the necessary heliocentric velocity. Errors in the observed direction of motion (apparent radiant) may be as small as a few minutes of arc, and those of speed V_∞ (velocity before sensible atmospheric retardation), less than 1%. The position of the meteoroid at the time of the observation is known with a precision unique in astronomy.

The orbits derived from the best observations have probable errors of the angular elements of $<1°$, and of e and 1/a, of the order of 0.05. The literature today contains orbital elements of this or somewhat less accuracy for approximately 1000 meteors (e.g., see Whipple, 1954; Jacchia and Whipple, 1961; Hawkins and Southworth, 1961; Babadzhanov and Kramer, 1967). Less accurate but useful orbits are known for an additional 2500 objects (McCrosky and Posen, 1961). The above references, while not comprehensive, include the major meteor-orbit catalogs. Most of this information has become available within the past decade.

The interpretation of these data, with regard to the ultimate aim of describing the origin and history of these small bodies of the solar system, has not progressed at the same rate. Certainly more information is currently

This research was supported in part by Grant NsG 291-62 from the National Aeronautics and Space Administration.

[1] Presented at the 33rd IAU Symposium on The Physics and Dynamics of Meteors, held in Tatranska Lomnica, Czechoslovakia, September 4-9, 1967.

available about orbits than about any other aspect of meteor astronomy and physics. Because of the ease and the precision with which orbits can be determined, observations in this field are well in advance of theory. I do not know of any reasonable surmise or hypothesis that requires for its verification either more or better orbits of meteors in the brightness range $-5 < M < 5$.

This is true, in part, because many of the most interesting questions of origins also involve questions of composition and structure. A full interpretation of orbits, then, depends on simultaneous physical observations and on an adequate physical theory of meteors.

Eventually, of course, histories and origins must be discussed in terms of planetary perturbations and physical effects that govern the lifetime of the particles. This will not be accomplished by extrapolating existing orbits into the past, but rather by locating an appropriate source in the solar system and by tracing it forward in time to demonstrate that what is now observed at earth is a reasonable expectation of all the processes that govern the past history of the material. The observed orbits may suggest a source of the meteoritic material, and they certainly supply the major boundary conditions to be met by any theory; but, in a very general sense, we investigate meteor orbits not so much to answer questions as to learn what questions to ask. However, none of this should suggest that orbits alone cannot give some specific insight to the problem of origin. For example, the association between meteor showers and comets is well known. More than half the showers recognized with certainty in photographic data are associated with known comets, and more than half the comets that might be expected to produce showers, say those with orbits approaching within 0.1 a.u. of the earth's orbit, have produced at least a few meteors. The comet-meteor relationship is unmistakable.

A second conclusive result from optical orbits relating to their origin is specified by the essentially complete absence of hyperbolic orbits. Jacchia and Whipple (1961) have placed an upper limit of 1% on the occurrence of such orbits and have amply demonstrated the soundness of this limit. Let me here take advantage of my special position as the producer of the largest number of photographic "hyperbolic" orbits to suggest that the primary value of such orbits is the determination of the accuracy of the observations and the reduction procedures, rather than the determination of the origin of the meteor.

For a variety of reasons, none of which may be valid, the asteroids have also been considered a source of meteors and, in particular, of meteorites. For these objects, we have been almost completely uninhibited by observations that might serve as boundary conditions. I have been attempting to fill that gap in our knowledge during the past 3 years. Very briefly, we have operated a 16-station network (Prairie Network) of cameras in the midwestern U.S. (McCrosky and Boeschenstein, 1965) that continuously observes an area of about 1.5×10^6 km^2. Each station contains four cameras (f/6 and 150-mm focal length) that together cover essentially the entire sky as seen from that station at elevations above 10°. The base line between the stations is 225 km. Chopping shutters and timing devices permit us to determine velocities and radiants with accuracies better than 1% and 0.5°, respectively.

I include in Table 1 in this paper 100 new photographic fireball orbits derived from these observations in the past 3 years. These data are for fireballs with maximum light between M = -5 and, perhaps, M = -18. The median value is M = -8.5. In general, these 100 objects represent the brightest and best observed of the present sample of 500 sporadic meteors that have been photographed. However, a few poorly observed but very interesting objects with substantially larger errors than quoted above have been included in the list and are so labeled.

The meteor duration also plays some role in the selection process. Meteors of duration less than 1 sec generally do not supply the timing information required for a good orbit, and a small percentage of objects

Table 1. Orbits of 100 fireballs

Meteor no.	Year	Month	Day UT	Note	True δ	Radiant α	V_∞	V_G	V_H	a	e	q	q′	ω	Ω	i	λ
39126	66	1	1.179		20.4	89.4	18.4	14.56	35.98	1.74	0.56	0.76	2.73	67.9	100.1	1.4	100.7
39128	66	1	3.494		37.0	13.9	13.4	7.55	36.87	2.00	0.51	0.98	3.02	188.3	282.5	5.6	147.9
39494	67	1	4.120		19.6	304.5	18.07	14.66	38.42	2.72	0.66	0.89	4.54	141.8	282.8	14.1	113.1
39129	66	1	4.271		7.8	40.7	13.0	7.25	36.81	1.98	0.50	0.97	2.99	15.0	103.2	1.5	151.5
39130	66	1	5.201		13.1	110.6	28.2	25.75	37.69	2.32	0.79	0.47	4.17	99.6	104.2	8.2	84.0
38768	65	1	8.209		1.6	88.5	17.7	13.74	36.88	2.00	0.58	0.83	3.17	52.9	107.5	8.5	107.7
39499	67	1	9.329		3.6	21.3	12.6	6.58	36.84	1.99	0.50	0.98	2.99	0.7	108.1	0.9	174.2
39135	66	1	10.137		16.6	119.7	28.8	26.25	36.78	1.97	0.78	0.42	3.52	107.4	109.2	3.9	80.7
39138A	66	1	13.354		9.6	124.5	24.93	22.40	33.76	1.33	0.66	0.44	2.23	111.7	112.5	8.4	78.0
39138B	66	1	13.496		30.5	136.8	30.8	29.00	35.24	1.58	0.80	0.31	2.84	301.8	292.6	17.0	72.7
39139	66	1	14.243		-40.0	76.5	19.6	16.32	38.89	3.06	0.68	0.96	5.15	18.6	113.4	22.0	109.5
39143	66	1	18.402		34.6	110.4	20.45	17.42	37.51	2.24	0.67	0.74	3.75	247.5	297.6	6.4	100.0
39512	67	1	22.406		4.6	134.8	20.2	17.08	30.87	1.04	0.52	0.50	1.59	115.7	121.5	7.7	75.6
39154	66	1	29.162		30.7	123.5	20.99	17.59	37.37	2.19	0.66	0.73	3.66	249.2	308.6	5.5	99.2
39169	66	2	13.352		35.4	149.1	22.88	20.15	37.55	2.30	0.69	0.69	3.91	253.6	323.9	13.0	94.3
39176	66	2	20.284		- 8.8	135.8	22.2	19.36	38.13	2.61	0.71	0.75	4.48	65.1	151.0	13.6	98.3
39179	66	2	23.175		0.6	155.6	23.4	20.36	35.21	1.60	0.64	0.57	2.64	94.3	153.9	6.2	86.0
39180A	66	2	24.160		43.6	108.2	14.5	9.31	37.34	2.23	0.56	0.96	3.50	201.7	334.9	5.2	135.7
39180B	66	2	24.334		- 6.4	148.1	20.4	17.26	35.16	1.59	0.56	0.69	2.50	80.4	155.1	9.9	91.6
39182	66	2	26.332		26.8	141.8	17.6	13.89	37.27	2.21	0.61	0.84	3.57	231.5	337.1	4.4	110.3
38827	65	3	8.451		43.9	207.5	29.4	27.30	36.87	2.08	0.64	0.73	3.42	250.1	347.5	39.5	79.8
39197	66	3	13.313		- 6.6	183.5	28.9	26.70	34.80	1.55	0.77	0.35	2.74	118.3	172.1	5.2	75.3
38469	64	3	15.293		-10.7	178.8	33.0	31.10	39.55	4.08	0.90	0.39	7.76	105.4	174.6	12.3	80.6
38847	65	3	28.109		-23.0	168.3	23.3	20.21	37.89	2.61	0.71	0.73	4.48	67.8	187.0	15.1	96.4
38850	65	3	31.255		- 1.0	190.6	25.1	22.45	37.08	2.22	0.73	0.58	3.86	269.3	10.1	2.5	89.0
38856	65	4	6.303		0.5	182.7	19.7	16.41	37.09	2.24	0.65	0.77	3.70	244.0	16.1	0.7	102.9
39224	66	4	9.244		-24.0	211.2	35.7	33.77	36.99	2.20	0.88	0.24	4.17	127.3	198.7	18.1	70.7
39229	66	4	14.207		- 5.1	183.4	18.1	14.30	36.65	2.09	0.60	0.83	3.35	57.1	203.6	1.4	107.5
39240	66	4	25.372		45.3	205.8	17.15	13.26	36.46	2.05	0.53	0.96	3.14	209.6	34.5	16.6	110.6
38880	65	4	30.228		35.0	257.2	18.80	14.89	29.14	0.97	0.22	0.75	1.19	291.4	39.5	26.2	73.7
38518	64	5	3.323		-30.7	217.1	28.23	26.03	38.47	3.19	0.82	0.54	5.84	90.5	222.7	13.4	87.3
39259	66	5	14.375		54.0	217.1	18.6	15.08	37.72	2.68	0.62	0.99	4.36	195.4	52.9	20.8	111.6
39625	67	5	15.180		-26.2	240.6	31.0	28.72	37.12	2.36	0.83	0.38	4.34	111.7	233.4	6.3	79.1
39261	66	5	16.379		65.8	356.7	20.2	16.71	31.86	1.20	0.32	0.81	1.58	102.0	54.8	27.5	82.4
39265	66	5	20.270		36.4	267.1	36.7	34.84	40.09	6.14	0.86	0.85	11.44	228.9	58.6	54.4	76.6
39276	66	5	31.318		- 9.5	247.4	25.8	23.43	38.08	2.97	0.79	0.60	5.34	264.7	69.2	9.3	91.4
38548	64	6	2.197		36.4	123.4	14.21	9.08	36.24	2.04	0.52	0.96	3.11	150.4	71.5	4.1	134.2
39296	66	6	20.183		-20.9	267.4	26.0	23.34	37.66	2.72	0.78	0.57	4.86	269.2	88.2	2.0	90.4
39302	66	6	26.305		70.9	284.8	30.0	27.87	38.58	3.47	0.70	1.01	5.93	171.8	94.0	45.9	84.9
39304	66	6	28.229		-23.5	274.3	24.3	21.52	36.96	2.34	0.74	0.60	4.09	90.8	275.9	0.1	91.9
39313	66	7	7.142		-11.3	303.0	37.6	35.62	38.53	3.43	0.93	0.21	6.64	308.5	104.4	16.1	71.9
39681	67	7	10.291		-34.7	283.1	20.84	17.68	35.84	1.93	0.63	0.70	3.16	78.0	287.1	6.6	96.1
39317	66	7	11.312		-25.2	289.0	18.6	15.04	33.47	1.42	0.51	0.68	2.15	87.4	288.3	1.4	92.2
39320 }	66	7	14.173	1,2	25.4	140.6	16.6	12.71	36.24	2.06	0.57	0.87	3.24	128.4	111.1	3.5	113.5
39320 }					26.9	142.2	17.8	14.26	37.43	2.59	0.66	0.87	4.31	129.6	111.1	4.6	114.3
39337	66	7	31.293		-41.4	338.5	38.6	36.88	41.45	32.30	0.98	0.44	64.2	97.7	307.4	41.8	76.4
39341	66	8	4.410		- 0.8	313.4	27.1	25.02	37.39	2.54	0.79	0.52	4.55	275.1	131.3	14.0	86.3
39349	66	8	12.143	7	57.1	45.0	61.0	59.81	41.55	40.20	0.97	0.96	79.4	153.9	138.8	114.4	39.5
39360	66	8	23.201		-17.9	16.6	24.0	20.93	24.74	0.77	0.66	0.25	1.29	149.4	329.4	25.0	55.6
39363	66	8	26.318		0.8	344.2	27.2	24.90	34.29	1.53	0.75	0.38	2.68	297.0	152.4	7.2	77.5
39000	65	8	28.284		- 0.6	309.8	17.9	14.25	37.30	2.44	0.65	0.85	4.02	232.6	154.5	6.9	112.1
39368	66	8	31.337		-10.5	333.3	21.0	18.01	36.32	2.03	0.66	0.67	3.38	259.1	157.3	0.3	96.6
39373	66	9	5.127		53.6	300.3	17.3	13.20	33.00	1.32	0.27	0.95	1.69	219.9	161.9	22.4	93.1
39376	66	9	8.167		-52.7	340.5	18.0	14.01	36.84	2.20	0.58	0.90	3.50	43.1	344.8	14.9	110.2
38651 }	64	9	13.099	1,2	-25.0	271.5	13.75	8.22	37.71	2.60	0.61	1.00	4.21	8.4	350.1	0.3	169.6
38651 }					-36.8	267.1	11.8	4.18	33.65	1.40	0.28	1.00	1.81	7.6	350.1	1.6	165.2
39382	66	9	14.099		79.3	303.8	33.7	31.80	37.37	2.42	0.58	1.00	3.84	190.2	170.6	55.2	74.9
39391	66	9	23.291		17.3	340.9	14.7	9.83	32.90	1.29	0.35	0.83	1.75	249.4	179.6	7.1	100.2
39031	65	9	28.136		- 8.7	359.7	20.52	16.90	36.52	2.03	0.64	0.71	3.35	74.0	4.6	4.1	99.2
39403	66	10	5.370		48.4	338.4	25.95	23.69	39.20	3.76	0.78	0.82	6.69	232.5	191.4	30.9	93.5
39405	66	10	7.120		-32.4	321.1	14.1	8.68	37.38	2.35	0.58	0.97	3.73	19.3	13.2	3.8	147.0
39406A	66	10	8.284		- 3.6	5.1	17.25	13.30	35.11	1.63	0.52	0.77	2.49	69.4	14.3	2.2	102.0
39406B	66	10	8.297		19.7	0.8	23.3	20.64	38.08	2.73	0.75	0.67	4.79	256.1	194.3	11.2	96.1
39043	65	10	10.101	4	55.4	259.9	23.7	21.12	38.98	3.46	0.71	0.99	5.94	170.6	196.4	32.1	98.5
39409	66	10	11.325		- 0.8	30.0	30.0	27.93	37.57	2.43	0.83	0.40	4.46	107.7	17.3	13.3	80.8
39411	66	10	13.197		65.5	223.0	33.74	31.97	39.10	3.58	0.73	0.95	6.20	153.5	199.2	52.2	78.5
39048	65	10	15.456		52.3	316.2	22.1	19.27	39.22	3.69	0.74	0.95	6.44	207.2	201.7	26.6	103.8
39049	65	10	16.123		9.7	36.9	31.8	29.46	36.42	1.96	0.84	0.30	3.62	121.4	22.3	6.1	75.5
39418	66	10	20.213		- 3.2	37.0	29.0	26.64	37.92	2.59	0.81	0.47	4.71	99.2	26.1	16.2	83.8
39057	65	10	24.099		-18.1	313.5	14.6	9.60	39.44	3.91	0.74	0.99	6.84	6.4	30.3	0.2	170.4
39423	66	10	25.223		23.8	44.8	34.5	32.51	37.27	2.25	0.89	0.24	4.26	306.9	211.1	10.5	72.9
39424	66	10	26.466		5.9	36.3	26.65	24.57	37.94	2.57	0.80	0.51	4.64	95.2	32.4	6.9	87.4
39060	65	10	27.112		73.4	246.2	31.5	29.59	38.08	2.66	0.62	0.99	4.32	179.8	213.3	49.8	79.5
39425	66	10	27.161		51.7	265.3	20.05	16.91	36.97	2.12	0.53	0.98	3.26	168.4	213.0	26.3	100.5
39065	65	11	1.174		15.8	44.1	17.31	13.00	31.22	1.09	0.43	0.61	1.56	103.7	38.3	0.4	82.9
39434	66	11	5.446	2	- 3.7	167.2	14.6	9.03	23.47	0.71	0.43	0.40	1.02	197.2	42.3	3.3	37.4
39442	66	11	13.104		18.7	54.2	24.8	21.87	35.53	1.67	0.70	0.50	2.85	100.8	50.0	0.6	84.5
39078	65	11	14.296		-38.4	282.4	10.8	0.29	30.29	1.01	0.02	0.98	1.04	12.3	51.5	0.1	135.7
39080A	65	11	16.135		86.6	230.7	32.6	30.66	37.51	2.30	0.60	0.92	3.68	215.1	233.4	51.6	76.2
39080B	65	11	16.253	3	22.7	152.5	72.5	71.33	42.14	52.6	0.98	0.98	104	172.1	233.5	161.8	10.8
39447	66	11	18.232		- 8.9	64.1	21.6	18.38	34.31	1.43	0.54	0.64	2.22	88.2	55.2	17.5	86.3
39450	66	11	21.243		27.2	55.8	25.6	23.02	37.74	2.39	0.77	0.55	4.24	270.9	238.2	5.6	89.2
39085	65	11	21.471	6	23.7	65.2	28.4	26.44	37.30	2.19	0.80	0.42	3.97	286.7	238.7	2.2	82.0
39086	65	11	22.464	6	24.3	66.3	28.5	26.55	37.33	2.20	0.81	0.41	3.99	286.9	239.7	2.7	81.9
39457	66	11	28.128		28.4	51.4	21.31	18.00	37.62	2.32	0.69	0.71	3.93	251.4	245.2	5.1	99.4
39093B	65	11	29.254		33.8	37.5	18.38	14.79	37.92	2.47	0.66	0.82	4.11	233.1	246.6	7.4	110.0
39093A	65	11	29.476	5	17.6	74.6	29.7	27.89	38.26	2.66	0.84	0.41	4.91	105.7	66.8	5.4	82.1
39094	65	11	30.372		4.5	118.1	61.0	59.94	42.57	-59.3	1.00	0.27	-119	116.5	67.7	131.5	41.8
39460	66	12	1.099	5	17.4	78.6	30.6	28.17	37.53	2.28	0.83	0.38	4.18	110.6	68.2	6.3	79.8
39462	66	12	3.415		17.9	52.3	18.7	15.42	37.69	2.34	0.66	0.78	3.90	59.5	70.6	0.4	106.7
38737	64	12	8.203		-21.0	98.3	17.14	12.71	29.13	0.93	0.29	0.65	1.20	117.5	75.9	18.5	72.7
38740	64	12	11.226		16.2	67.0	17.36	13.29	35.40	1.62	0.52	0.77	2.46	67.3	79.0	2.2	101.5
39470	66	12	11.050	2	24.1	75.7	23.6	20.46	37.22	2.13	0.71	0.61	3.66	265.1	258.8	0.8	92.2
39474	66	12	15.073		- 3.2	318.3	14.3	9.38	38.30	2.65	0.63	0.96	4.34	161.6	262.4	3.0	145.0
39476	66	12	17.170		8.8	76.9	20.16	16.62	36.52	1.89	0.61	0.72	3.07	71.8	84.5	7.1	97.9
39113	65	12	19.252		37.0	45.3	15.03	10.30	36.74	1.96	0.53	0.91	3.01	217.8	266.9	5.4	121.5
39115	66	12	21.457		26.2	85.7	21.6	18.83	36.60	1.91	0.66	0.64	3.18	262.4	269.2	1.7	93.2
39116	65	12	22.437		75.7	221.7	35.2	33.32	40.74	6.25	0.84	0.94	11.57	204.6	270.2	52.3	79.5
39120	65	12	26.296		61.5	89.6	23.0	20.19	37.46	2.22	0.66	0.75	3.68	245.3	274.1	21.5	93.5
39121	65	12	27.348		15.5	94.9	23.75	21.16	37.16	2.10	0.71	0.59	3.61	86.6	95.2	5.4	90.6
39122	65	12	28.138		39.3	84.9	22.6	19.49	38.75	2.94	0.75	0.72	5.17	247.8	276.0	9.0	99.8
39125	65	12	31.324		45.4	94.8	22.0	19.11	37.30	2.15	0.67	0.70	3.61	252.9	279.2	12.6	95.3

1. Poor observations; the two orbits listed represent probable extremes
2. Detonating bolide
3. Leonid
4. Draconid
5. S. Taurid
6. N. Taurid
7. Perseid

that are bright but of short duration have not been reduced. Readily identified shower meteors have also been excluded unless they were of exceptional brightness or duration. It is true, however, that most shower meteors are of less than 1-sec duration and would be rejected for that reason.

An additional bias in the observations is introduced because of the great base line between the stations and the concomitant importance of large atmospheric absorption affecting the meteors at large zenith distances. Because of their greater altitude, high-velocity objects have a substantially better chance of being observed from two stations. Meteors of low luminosity and near the limit of our system can be photographed from two stations only if they occur in a rather small region, about half way between two of the stations. These biases can be accounted for with some accuracy when our statistics warrant it; they are not important for the present analysis.

In the absence of reliable velocity information on very bright objects, Whipple and Hughes (1955), following the work of Newton (1888), analyzed the elongations of the geocentric radiants λ of these bodies. Whipple and Hughes compared the frequency distribution for various brightness classes of objects: photographic meteors, $M \approx -2$ (small-camera meteors); fainter fireballs, $M \approx -5$; great fireballs, $M \approx -12$; detonating bolides; and meteorite-producing events. The distributions could be considered bimodal, with the minor mode at $\lambda = 40°$ becoming progressively weaker with increasing brightness and disappearing altogether for the bolides and meteorites. The median value of λ for the major mode increased from 90° to 130° with a convincing, if not perfect, regularity as the event brightness increased. The authors, at least by implication, suggested that the major mode was comprised of two distribution functions derived from separate sources. One distribution source, with a slightly larger mean value of λ, becomes progressively more important with increasing body size, thus producing the observed trend.

The simplest explanation for the distributions is that there are three sources of meteors, each with its own number-magnitude relationship.

Whipple and Hughes suggested, as a working hypothesis, the asteroids as a source for the meteorites, and long-period comets as a source for the objects of small elongation. Short-period comets are the source for the majority of the photographic meteors. We can extend the accurate data to both brighter and fainter objects today.

The data on the faintest photographic meteors have been obtained from the Super-Schmidt meteor cameras of the Harvard Meteor Project. The distribution of the Super-Schmidt sporadic meteors, as derived from McCrosky and Posen meteor data, is shown in Figure 1. The fact that the low elongation peak does not stand out so clearly as it did in the small-camera photographic data may be significant, but it is more likely a result of the often-noted selectivity employed in choosing meteors for reduction from the small-camera data. The blending together of the two groups in these newer data makes the distinction between the two classes less obvious than before, but in fact, new information on the physical characteristics of these bodies from the Super-Schmidt material makes it easier to distinguish the two groups. Jacchia (1958) has shown that there is a significant difference in the beginning heights of meteors in these two classes. Jacchia chose as the dividing line between the two groups an aphelion distance of 7 a.u. Verniani (1964) has demonstrated that the bulk densities of these two classes are also statistically different.

Additional evidence of a distinction between the two classes of orbits is given by the distribution of elongation for the Prairie Network objects in Figure 1. The remarkable cutoff at $\lambda = 70°$ in the fireball data is not apparent in the visual data assembled by Whipple and Hughes, but this is almost certainly a result of the larger observational errors in that material rather than of a real physical effect. The Prairie Network data, diffused by a normal error function with a standard error of 10°, closely resemble the distribution of the great fireballs given in the visual observations.

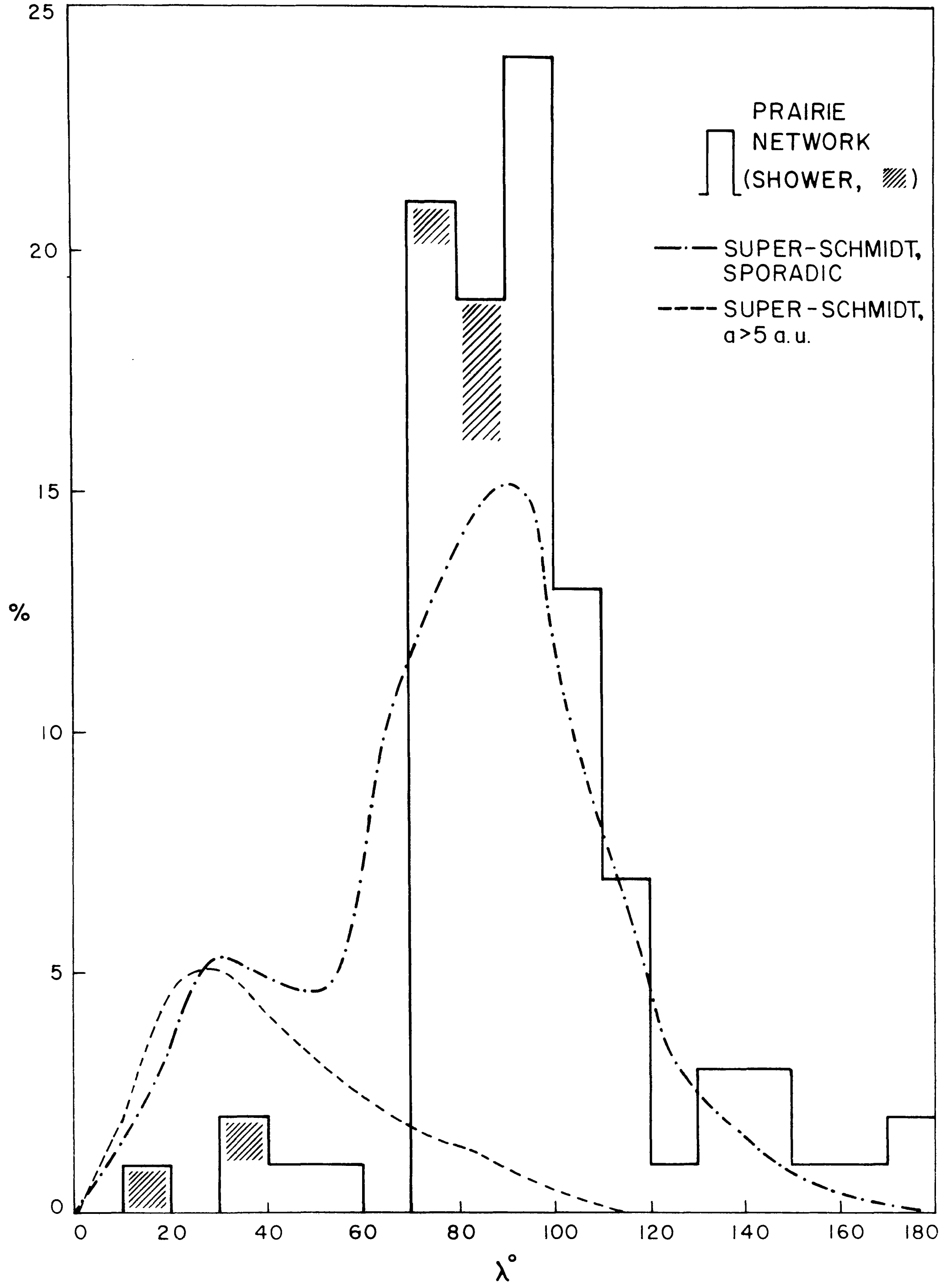

Figure 1. Distribution of geocentric elongation of radiant for Prairie Network, McCrosky-Posen sporadics, and Hawkins-Southworth large orbits.

Any uncertainty that may have arisen from the visual data that Whipple and Hughes were forced to use has been removed. The number-magnitude relationship for the two classes of orbits is sufficiently different to suggest that either different origins or different histories are involved. The problem would be greatly simplified at this point if we could somehow demonstrate that comets and asteroids were the respective sources of the two groups. (Note that the distributions of elongation in the Prairie Network and the meteorite data of Whipple and Hughes need not be similar, even though the objects are derived from the same source in the solar system. The Prairie Network observations, necessarily limited to nighttime hours, should be expected to peak at a lower elongation.) However, the exhaustive work of Jacchia, Verniani, and Briggs (1965) demonstrates that this is not true for smaller objects. Since we can divide the faint meteor data into two groups by some rational means and can demonstrate that the distributions of orbital elements of these faint meteors and the bright meteors are similar, there is even less motivation for making the gross assumption that bright objects are of asteroidal origin.

Figure 2 is a plot of the Jacchia and Whipple orbits as a function of elongation and heliocentric velocity, in which we can readily see the distinction between the two groups. I have chosen $V_H \approx 39.8$ ($a \approx 5$ a.u.) as a reasonable dividing line. The absence of meteors of large a and large λ simply demonstrates that brightness is a strong function of geocentric velocity. The smoothed distribution of λ for large orbits as taken from the statistical sample of Super-Schmidt data of Hawkins and Southworth is shown in Figure 1.

The small orbits, in the triangular array at $\lambda > 55°$ in Figure 2, are direct orbits of low inclination. The physical limit of perihelion distance imposed by the sun's radiation is shown by the line on the left; a second seemingly significant limit is shown at $q = 0.2$ a.u., beyond which only a few sporadic objects and the Geminids, δ Aquarids, and Quadrantids occur. Figure 3 is a similar plot of the Prairie Network data.

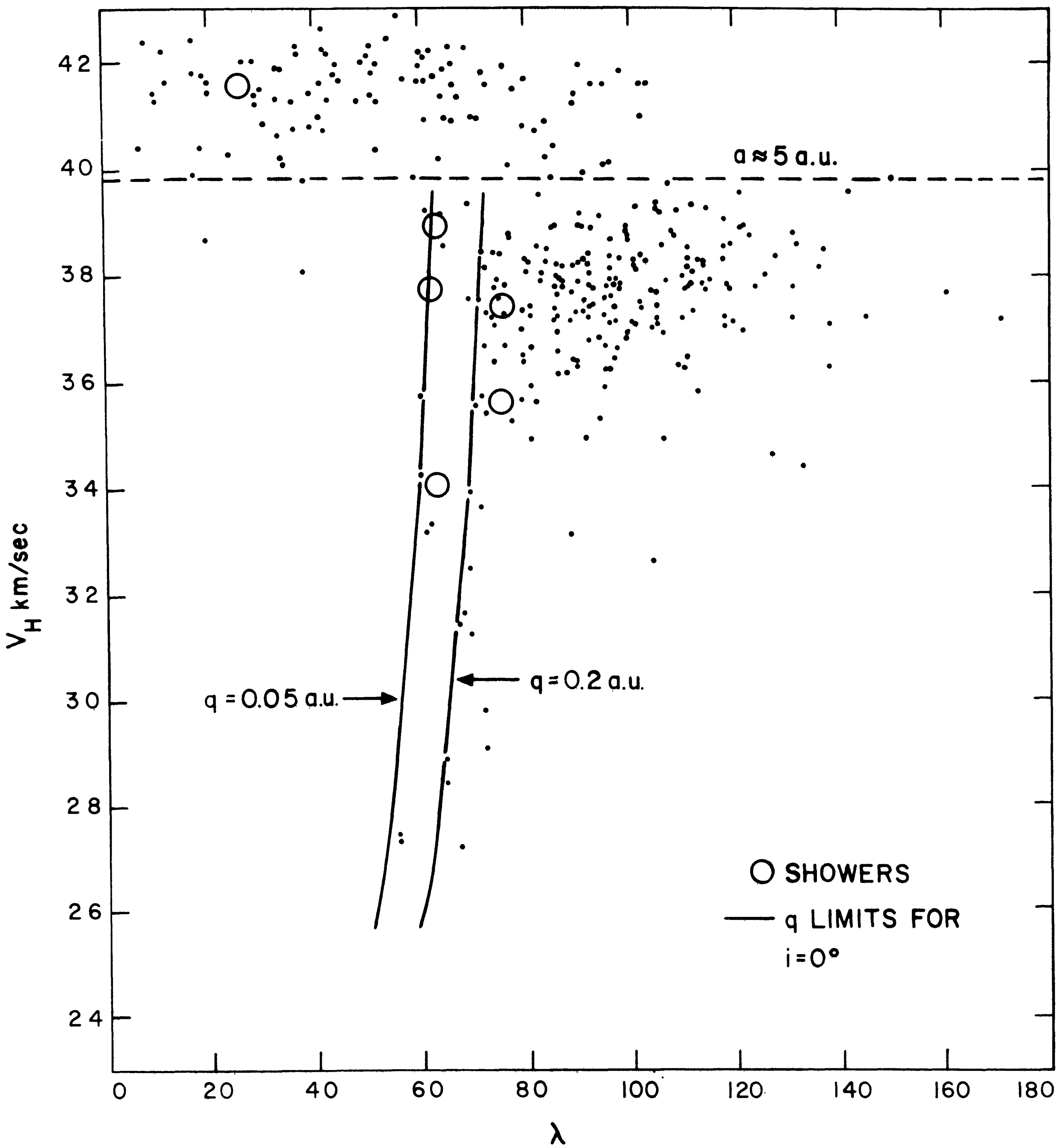

Figure 2. Geocentric elongation of radiant versus heliocentric velocity for Jacchia-Whipple precision orbits.

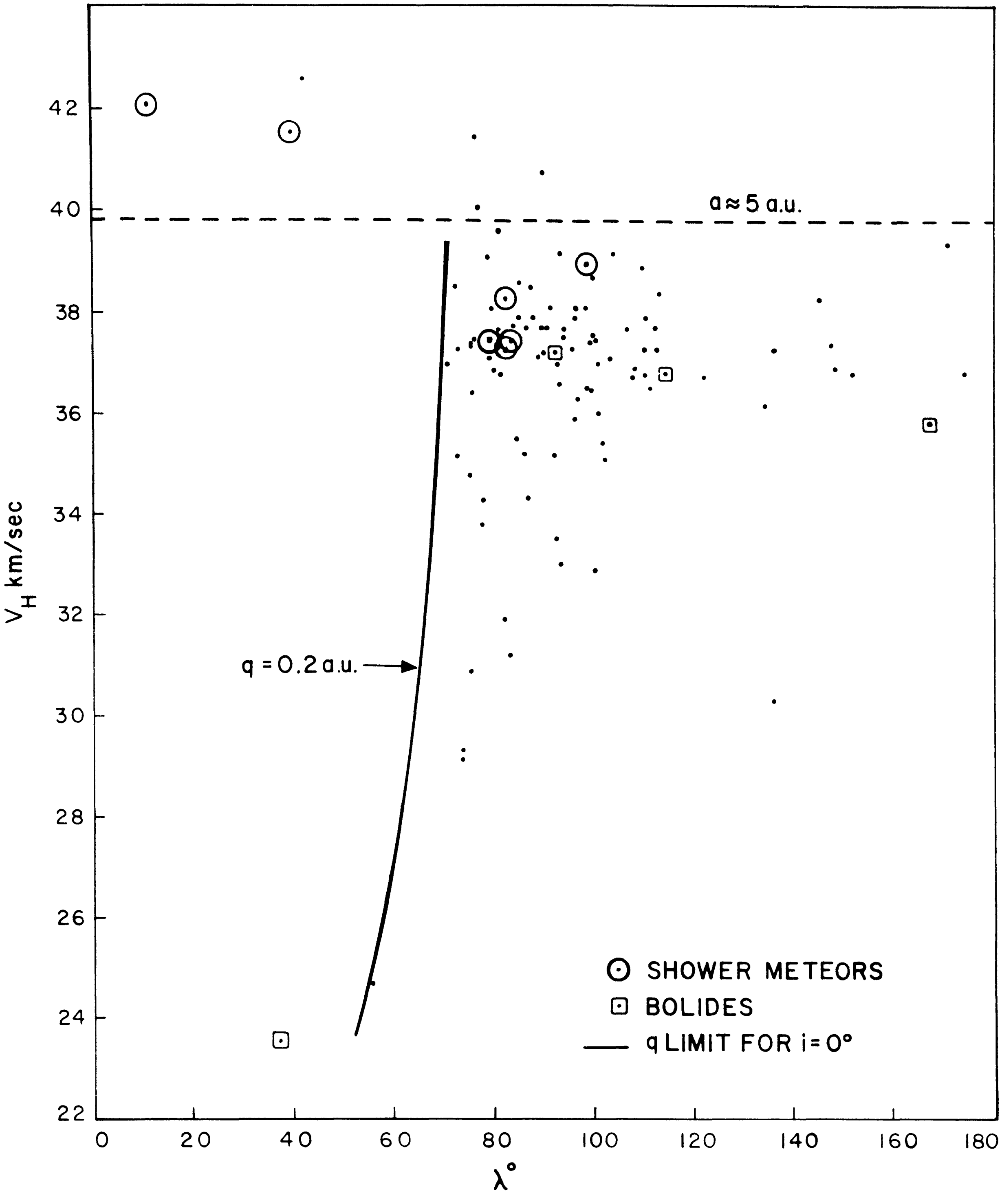

Figure 3. Geocentric elongation of radiant versus heliocentric velocity for 100 Prairie Network orbits.

By limiting the observations to fireballs, we can almost eliminate the low-elongation group. To search for orbital differences between faint meteors and the fireballs of small a, I compared the Hawkins-Southworth sporadic meteors with $a < 5$ a.u. with the similar group of Prairie Network objects. Figure 4a, presenting the distribution of inclinations, shows no suggestion of a significant difference between the two brightness classes. The median value of inclination for each of these groups is of the order of 10°, about half that of the value for the distribution of all Super-Schmidt meteors.

Figure 4b shows the distribution of aphelion distances. The considerably greater tail of objects with aphelia outside Jupiter's orbit for the fainter meteors should perhaps be interpreted as a result of our simple and inexact dividing line between the two groups; i.e., nature has divided the objects more carefully by brightness than I have been able to do by their orbital elements. In any case, the difference between the two distributions is almost certainly more exaggerated than is shown in the diagram, since a number of Prairie Network meteors with $q' > 5.2$ must result from some observational error and diffusion from the substantial peak at smaller values of q'. Indeed, the decrease in the number of orbits with aphelia just beyond Jupiter is sufficiently striking to suggest that $q' \approx 5.2$ a.u. may represent the most significant dividing line between two types of objects.

In Figure 4c it is seen that although the eccentricities follow the same general trend, brighter objects have slightly less eccentric orbits on the average. Again, this probably indicates some contamination in the selection of faint meteors. The similarity between the two eccentricity distributions is more remarkable than their differences.

It is in the perihelion distances, Figure 4d, that we see the greatest similarity between the two distributions. The peak near $q = 1$ is, of course, due to an observational selection effect, associated with the high probability of collision with the earth for bodies with this perihelion distance. If these curves were corrected for this bias, they would both show a gentle rise from 0 to 0.75, followed by a sharp decline to $q = 1$. This is certainly the major

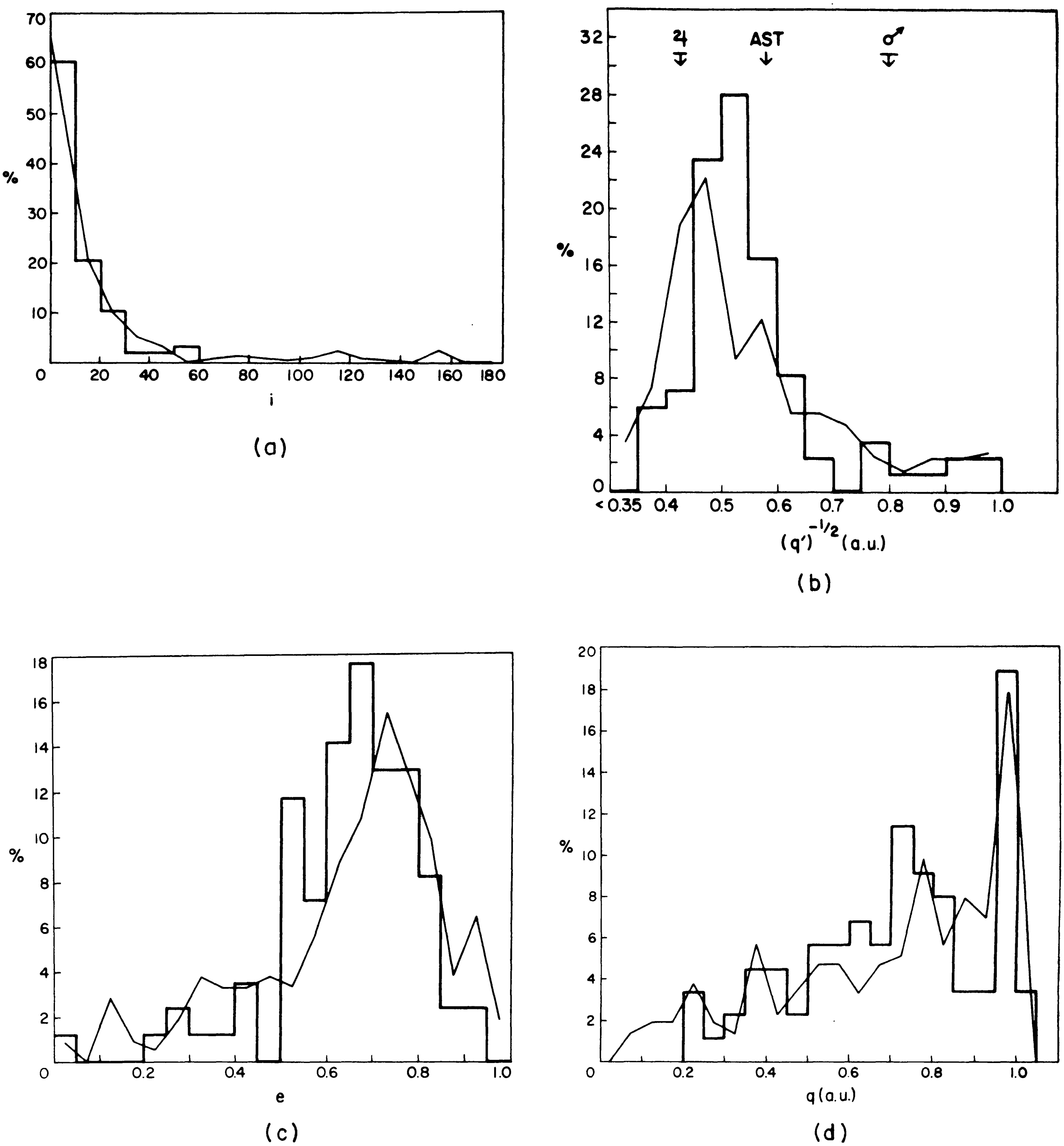

Figure 4. Distribution of orbital elements of Hawkins-Southworth (/\) and Prairie Network (⌐|) meteors with $a < 5$ a.u. for: (a) i, inclination; (b) $(q')^{-1/2}$, q' = aphelion distances; (c) e, eccentricity; and (d) q, perihelion distances.

characteristic of these orbits that requires explanation. All the earth-crossing asteroids except Adonis and Icarus have perihelia between 0.65 and 0.89. Whether or not the Apollo asteroids are generically related to the fireballs, it seems probable that these two groups of objects have something in common in their histories. Incidentally, the distribution of perihelion distances for Super-Schmidt meteors as a whole shows the number of meteors increasing monotonically and almost parabolically with increasing q. By eliminating large orbits, we have preferentially eliminated a large number of those with $q > 0.8$.

The small peak in both distributions in the vicinity of $q = 0.4$ may be associated with an extended Taurid shower. The fireball data include a number of objects, occurring as late as mid-January, with values of q and e appropriate for either of the Taurid streams. I am reluctant to be definite about this association until such time as we have more data on objects occurring in December and January that may permit us to demonstrate a general trend in the elements and the radiant.

The absence of fireballs with $q < 0.2$ is associated with the absence of objects with elongation between 60° and 70°. As yet, our data are too few to be certain that the absence is statistically significant.

In summary, the difference between the distributions of elements of the bright and faint class group II objects does exist, but the similarities are even more striking. It will require strong evidence to the contrary for me to refrain from concluding that these two groups of objects, the faint Super-Schmidt meteors of $a < 5$ (or, perhaps, $q' < 5.2$) and the bright fireballs with similar-sized orbits, do not have a generic relationship.

There remains the possibility that the fireball orbits are only by coincidence similar to the short-period faint meteors and that they are, in fact, derived from different sources. In support of such an argument, we can note that the mean value of $1/a$ increases with increasing magnitude for Super-Schmidt data (Kresák, 1964) or that, when comparing either of the small-camera meteor samples (Whipple, 1954; Babadzhanov and Kramer, 1967), with Super-Schmidt data, the same kind of effect is seen. However, both such comparisons are made on a relatively short base line of brightness where any slight selection effect may prove disruptive to the analysis. Of course, it is not impossible for the derivative of the ratio of large to small orbits to change sign, but it is somewhat disturbing to find that this happens to occur at just that point on the magnitude scale where meteor observations are relatively easy to make.

If the fireballs are derived from a different source — particularly from asteroids — the difference will be detectable in the physical characteristics (Cook, Jacchia, and McCrosky, 1963). A major purpose of the Prairie Network is to bring under observation high-density asteroidal material in an attempt to learn something of their orbits and origin and to improve our understanding of the physics of the atmospheric-entry problem by investigating material of relatively well-known density and with some structural integrity. These statements imply a number of assumptions that are not uniformally agreed to, for example:

A. "Brighter, and presumably larger, meteors will give a better sample of high-density asteroidal material." There is no certain observational evidence to confirm this.

B. "High-density objects, and particularly meteorites, are of asteroidal origin. Low-density material does not produce meteorites and is derived from comets." Although I wish to discuss apparent densities of these bright meteors, I see no requirement in the present data that impels us to reject Öpik's (1965) cometary origin for meteoritic stones, or similarly to reject an asteroidal origin (Whipple, 1967) for some material of weak structure or even of low density. In short, my comments on structure are not to be construed as comments on origin.

C. "Trajectory and luminosity data of large bodies can be treated within the framework of faint-meteor physics." I do not believe this statement in detail, but I will, in a later paper, present arguments to substantiate my view that the existing theory offers a reasonable starting point to which perturbations to the present theory can be applied.

I will present here only a summary of preliminary results for 28 of the meteors for which orbits are given. Complete photometry and trajectory data are available for these and will be published in their entirety elsewhere. Because of the increased range and poorer quality optics, neither the trajectory data nor the photometry data can compare with the Super-Schmidt material. Nevertheless, photometry is thought to be accurate to 0.5 mag, on the average. The long lifetime of the meteor makes up in part for the poorer measures of trajectory. Decelerations determined over trajectory arcs of from 1 to 2 sec of time have internal probable errors of 10% of the value of the deceleration.

Let us combine the drag equation and the photometric mass equations,

$$\nu = \frac{m}{A} = \frac{\Gamma \rho V^2}{\dot{V}}$$

and

$$m = \frac{2}{\tau_0} \int_0^T \frac{I}{V^3} \, dt \quad ,$$

where m = mass of meteoroid, A = frontal area, $\Gamma = 0.46$ = drag coefficient, ρ = atmospheric density, V = velocity, $\dot{V} = dV/dt$, τ_0 = luminous efficiency, and I = intensity (M = -2.5 log I). The integration is performed over the duration of the meteor, T. If we further assume the body to be spherical, we can formally derive a bulk density, δ:

$$\delta = \left(\frac{\sqrt{\pi}\ \nu^3}{m} \right)^{1/2} \quad .$$

This density is an upper limit, insofar as the terminal mass of the body is assumed negligible. When more than one determination of δ can be made for a meteor, either from separate photographs or from different portions of the trajectory, the agreement of the values is not outstanding. Variations by a factor of 3 are observed, presumably reflecting the great weight placed on ν, which depends on the second derivative of the observations. The remarkable fact is, however, that of these 28 meteors, including over 100 density determinations, none yielded a density, as determined by equation (3), in excess of 1.2 gm cm^{-2}. The average value of about 0.4 is essentially the same as that determined by Verniani for Super-Schmidt meteors. If we wish to believe that an appreciable fraction of meteors of -8 mag have high densities, it would appear that we must call upon either a similar error in the theory and analysis applicable to both faint and bright meteors or we must resolve the problem by detecting errors in the bright-meteor analysis that, by chance, produced dust-ball densities.

It is unrealistic to suggest that the value of luminous efficiency used, as derived from observations of natural and artificial meteors, is in error by 2 orders of magnitude or that the shapes of these objects depart from a sphere to such an extent that the observed densities are underestimated by a factor of 10. Nor is it likely that the values of deceleration can be systematically in error by a factor of 5. Although a smaller contribution from each of these possible errors could conceivably cause us to determine a gross underestimate of the density, it appears more prudent to accept the fact that most large meteor bodies do not differ substantially in their structure from small bodies. If this is the case, then our data suggest that, over the area of the Prairie Network each year, one such low-density object with a terminal mass of the order of 5 kg should reach the ground. If the object can withstand impact, survive any rain that occurs prior to discovery, and be recognized, I believe we have a reasonable chance of recovering the meteorite. The argument concerning its asteroidal or cometary origin can then continue unabated.

ACKNOWLEDGMENTS

Of the numerous people who have been responsible for the acquisition and reduction of the data presented here, a special recognition is due to two individuals: Mr. C.A. Tougas, who supervised the establishment of the Prairie Network, and Mr. Gunther Schwartz, the present manager of the Network, who has contributed notably to every Harvard and Smithsonian meteor-research project for the past 20 years.

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BIOGRAPHICAL NOTE

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Dr. McCrosky received his B.S. degree in physics from Harvard University in 1952, and his Ph.D. in astronomy from that university in 1956.