METEORITE ORBITS FROM OBSERVATIONS BY CAMERA NETWORKS

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Camera networks for the study of bright fireballs now have a history approaching two decades. It was hoped that the networks would produce a statistically significant group of recovered meteorites with accurate orbits. Due to the great difficulty in locating the meteorites from a photographed event, there are still only three meteorites with orbits determined from suitable photographs; Pribram, Lost City and Innisfree (Ceplecha 1961, McCrosky et al. 1971, Halliday et al. 1978, respectively). Networks do, however, provide an alternative approach to the problem. Instead of determining approximate orbits from visual observations of recovered meteorite falls, it is now preferable to use reliable orbits from the camera networks for fireballs which are believed to have dropped meteorites that could not be located, or, that are believed to have been physically identical to meteorites, although no appreciable mass survived the atmospheric flight. This paper will review current knowledge based on this approach to the problem.

Elements of the three reliably determined orbits are listed in Table 1 and a projection of these orbits on the ecliptic was shown as Figure 8 in Halliday et al. (1978). Pribram and Lost City are both H5 chondrites while Innisfree is an LL5-6 chondrite. Table 1 appears to support earlier conclusions that meteorite orbits are low-inclination, direct orbits with aphelia between Mars and Jupiter.

Let us examine three groups of fireballs, one from each of the major networks, designated PN (Prairie Network, U.S.A., operated 1963 - 1975), EN (European Network, Central Europe, in operation 1964 - present), MORP (Meteorite Observation and Recovery Project, Canada, 1971 - present). McCrosky et al. (1976, 1977) published orbits and photometric data for more than 320 PN fireballs. They stress that the data are not a random sample and should not be used for many statistical purposes, including "the orbital distribution of mass or magnitude classes". Wetherill and ReVelle (1981) have examined this data to select a group of fireballs which resemble the three fireballs of the recovered meteorites in Table 1 and are thus believed to represent ordinary chondrites which were not found.

Richard M. West (ed.), Highlights of Astronomy, Vol. 6, 399–404.

https://doi.org/10.1017/S1539299600005396 Published online by Cambridge University Press

Table 1

	Pribram	Lost City	Innisfree
Date	1959 Apr 7	1970 Jan 4	1977 Feb 6
U.T.	19:30	02:14	02:18
a, AU	2.42	1.66	1.87
e	0.674	0.417	0.473
i	10.4°	12.0°	12.3°
ω, arg. of perihelion	241.6	161.0	178.0
Ω, long. ascending node	17.1	283.0	316.8
q, perihelion dist.	0.790	0.967	0.986
q', aphelion dist.	4.05	2.35	2.76
v_∞, entry vel. km s^{-1}	20.9	14.2	14.5

The second group of fireballs are those observed by the MORP network that are believed to have produced surviving meteorites of at least 50 grams for the largest fragment. The mass estimates are based on dynamical masses derived from velocity and deceleration values during the final half-second of the luminous trail, using an assumed brick-like shape to convert mass-to-area ratios to mass, calibrated from recovered fragments of Innisfree. Table 2 lists the MORP number, Julian Date, selected orbital elements, entry velocity v_∞ and end velocity v_E in km s^{-1}, the dynamical mass of the largest fragment, m_d, in grams, and the end height, H_E, for the 50 fireballs of this group.

The third group contains fireballs observed by the EN described as Type I, where Type I was defined by Ceplecha and McCrosky (1976) as the group with the behavior expected of ordinary chondrites. Data on 22 Type I fireballs were collected from: (1) a list of 42 fireballs (Ceplecha 1977) that includes several photographed before the EN was in operation; (2) a list of 29 fireballs photographed in 1977 (Ceplecha et al. 1982); (3) data on recent EN fireballs in the SEAN Bulletin (Scientific Event Alert Network) Smithsonian Institution, Washington, D.C.

Considerable information on orbits can be exhibited in plots as in Figure 1, which plots a vs e for the three groups of fireballs. The curved line running up and to the right defines the locus of orbits with perihelion at 1.0 AU while the line toward lower right defines orbits with aphelion at 1.0. Earth-crossing orbits are thus confined to the area between these lines (except for minor effects due to eccentricity of the earth's orbit). Large orbits fall in the upper part of the plots with Aten-type objects (a <1.0) near the bottom. Objects crowding the curved lines move nearly tangentially to the earth's orbit at the time of impact but those which fall far to the right may cross the orbit of Mercury.

Inspection of the three plots indicates that the PN fireballs selected by Wetherill and ReVelle cluster close to the lines defining the permitted area, in fact half of them have q >0.95. This clustering is less marked for the MORP fireballs and is not pronounced at all for the EN group. The ten MORP objects with masses exceeding 1 kg in Table 2 are shown with crosses in Figure 1. Although they are few in number, they

https://doi.org/10.1017/S1539299600005396 Published online by Cambridge University Press

show as strong a concentration to large perihelia as do the PN fireballs.

Figure 1 contains no information on inclinations of the orbit planes. The mean values of inclination are 7.7° for PN, 8.2° for MORP and 14.0° for EN. Median values are insensitive to an occasional extreme value and these are 5.5° for PN, 6.0° for MORP and 10.1° for EN. The PN and MORP values are similar, with many small inclinations, while the EN fireballs show nearly twice the orbital inclinations of the other groups.

What differences in the manner of selection of these groups lead to the differences in Figure 1 and in the inclinations? The criteria used by Wetherill and ReVelle to select ordinary chondrites from the PN data are relatively strict, i.e. they may be expected to omit some normal chondrites rather than include more fragile material. Half the values in the PN plot in Figure 1 are from their Table VI, in which the entries must meet all four criteria, and the other half are from Table VII, which generally fail to meet one criterion. All of these fireballs satisfy the criterion that the meteor was observed down to an end velocity of 8.0 km s^{-1} or less. There is a selection effect here which tends to exclude small meteorites. From a study of the separate photographic trails of recovered fragments of Innisfree, Halliday et al. (1981) found that ablation was unimportant as a source of luminosity below 10 km s^{-1}. The luminosity is then due to energy in the shock wave derived from decreasing velocity rather than mass loss. Small meteorites (a few hundred grams) appear to be considerably less efficient as luminous sources low in the atmosphere than large ones, so the 8 km s^{-1} limit may remove small but genuine meteorites from the sample.

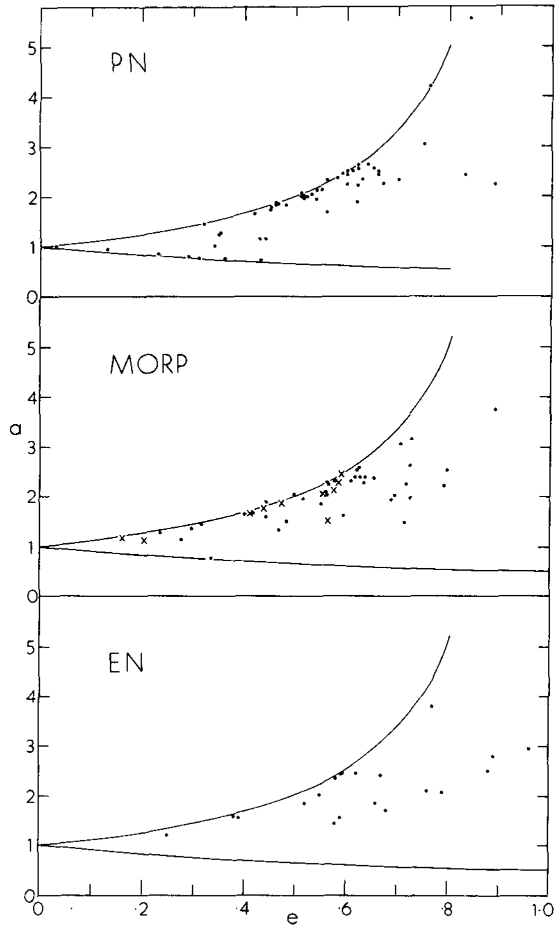

Fig. 1. Plots of a vs e for three groups of fireballs.

The dynamic pressure on a meteorite in flight varies as the square of the velocity, hence faster meteorites will fragment more easily and the small dust particles released during any fragmentation process are consumed quickly, producing a bright flare or even a flash. For example, the Peace River chondrite fall includes three fragments of 10 kg each, so it was far from being consumed in flight. One eyewitness, describing the fireball,

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Table 2. Data on 50 MORP fireballs

MORP	JD2440000+	a	e	q	q'	i	v_∞	v_E	m_d	H_E
1	0798.835	3.76	.892	0.405	7.1	1.7	31.3	11.3	960	29.7
18	1181.708	2.28	.634	0.837	3.7	3.5	18.1	5.7	300	27.8
111	2142.920	2.60	.760	0.624	4.6	0.3	24.4	11.5	90	35.8
123	2271.790	2.01	.563	0.877	3.1	3.1	16.4	8.7	740	32.6
129	2306.845	2.21	.791	0.461	4.0	4.4	27.3	12.5	240	33.8
138	2356.825	3.07	.707	0.901	5.2	9.0	17.4	9.4	75	37.0
163	2447.990	2.39	.627	0.891	3.9	15.3	18.6	6.5	60	30.5
169	2483.874	2.62	.726	0.729	4.5	13.7	22.9	10.6	280	34.0
171	2504.781	1.89	.444	0.661	1.7	3.9	18.1	7.5	160	33.7
172	2513.744	1.27	.236	0.970	1.6	5.1	12.5	8.1	620	31.2
174	2542.892	2.05	.555	0.913	3.2	19.9	19.1	12.3	1200	32.3
189	2669.831	1.93	.518	0.928	2.9	1.5	14.5	4.8	180	27.9
193	2677.672	3.15	.728	0.858	5.4	23.2	22.7	10.0	55	33.0
195	2681.758	1.98	.726	0.541	3.4	3.5	24.6	10.8	160	31.7
204	2729.673	1.12	.205	0.890	1.4	7.2	13.0	6.6	1300	29.5
207	2732.790	2.39	.638	0.865	3.9	11.0	17.9	6.5	560	25.9
219	2758.700	2.38	.655	0.822	3.9	1.0	18.2	6.7	110	29.1
223	2763.111	2.51	.798	0.506	4.5	7.2	27.1	9.5	930	26.3
227	2781.838	2.40	.619	0.912	3.9	7.7	16.1	11.0	65	37.0
231	2812.703	1.48	.715	0.423	2.5	17.4	27.9	12.6	180	34.2
241	2877.788	2.32	.610	0.903	3.7	4.8	16.7	8.6	55	34.9
245	2950.831	2.02	.499	1.013	3.0	6.5	13.5	9.0	120	38.9
261	3083.583	1.69	.414	0.992	2.4	0.8	12.4	7.8	520	34.4
268	3122.583	1.83	.561	0.804	2.9	5.4	19.1	15.9	250	42.9
285	3180.596	1.87	.473	0.986	2.8	12.3	14.5	2.7	1700	19.8
287	3181.808	2.25	.717	0.637	3.9	2.1	23.4	10.5	100	33.1
288	3191.809	1.76	.438	0.987	2.5	1.0	12.4	4.1	6200	20.2
299	3239.901	2.01	.697	0.610	3.4	3.7	23.6	14.4	160	35.7
303	3248.942	2.29	.562	1.003	3.6	8.1	14.1	8.2	110	34.9
305	3253.772	1.65	.401	0.991	2.3	18.8	16.4	8.8	80	29.6
307	3264.879	1.51	.563	0.661	2.4	11.9	21.0	3.8	1200	22.0
331	3441.882	0.76	.338	0.501	1.01	3.2	13.3	5.8	650	30.9
341	3463.522	1.66	.411	0.976	2.3	2.4	12.8	8.5	1600	31.9
345	3469.963	1.33	.469	0.705	2.0	5.3	17.4	10.6	210	34.3
346	3469.709	1.60	.443	0.892	2.3	11.5	15.7	8.5	120	31.0
348	3472.578	2.08	.557	0.920	3.2	0.1	15.0	8.7	70	36.1
364	3597.653	1.17	.162	0.984	1.4	1.5	11.3	5.3	1400	25.4
368	3623.867	2.30	.580	0.965	3.6	24.6	20.1	10.4	85	34.3
425	3797.968	1.12	.278	0.809	1.4	20.7	17.2	11.8	85	37.2
511	4197.587	2.59	.624	0.973	4.2	19.4	18.1	9.8	150	31.7
540	4258.674	1.35	.298	0.950	1.8	0.8	12.4	6.9	65	40.7
544	4273.885	2.29	.586	0.947	3.6	2.6	14.5	6.7	5900	25.8
567	4426.892	1.94	.690	0.601	3.3	7.0	23.4	9.7	270	35.0
580	4483.840	2.45	.591	1.000	3.9	6.5	14.2	5.2	11000	28.0
591	4492.667	1.61	.596	0.652	2.6	0.3	20.4	12.4	100	38.3
626	4568.621	2.26	.567	0.980	3.6	1.2	13.5	10.8	590	33.5
669	4694.747	2.56	.621	0.969	4.2	25.3	20.6	8.6	120	30.6
683	4791.875	1.49	.483	0.769	2.2	7.8	17.6	9.1	230	33.1
687	4985.642	2.11	.577	0.892	3.3	11.1	16.7	5.9	1600	28.9
771	4969.983	1.44	.317	0.982	1.9	21.7	17.1	9.0	160	31.0

https://doi.org/10.1017/S1539299600005396 Published online by Cambridge University Press

stated "Then came a flash so brilliant that you could not see anything and it lit up everything bright as day" (Folinsbee and Bayrock 1964). This irregular light curve would cause the fireball to fail one and possibly two of the criteria of Wetherill and ReVelle, presumably because the velocity was higher than for Lost City and Innisfree. In addition to the warning by McCrosky et al. (1976) that the PN data may not be suitable for orbital distributions, it seems likely that the criteria used to isolate the ordinary chondrites may discriminate against small meteorites and against fireballs that are faster than average.

The MORP fireballs in Figure 1 and Table 2 include all cases from this network in which a surviving main mass of 50 grams or larger is expected (except for very recent events and a few unspectacular earlier events where reductions are incomplete). There should be less reason to suspect serious selection effects than in the PN data. One third of the fireballs penetrated below 30 km but half the entire group have end heights between 30 and 35 km. In some cases, better observing conditions (improved transparency or reduced range from the cameras) would have lowered the end heights considerably. Fireballs terminating above 30 km may not inspire the confidence in a meteorite fall that is required to justify the effort of a ground search, but they are capable of dropping at least small meteorites. Although small falls are normally not located, the remarkable recoveries from Antarctica suggest that the most common meteorite mass is about 15 grams (Olsen 1981) rather than a few kilograms as would be inferred from more normal recoveries (Hughes 1981). Admittedly, some of the fireballs in Table 2 which disappeared at relatively large heights may not have dropped a substantial mass, but most of them probably are associated with real meteorites of at least "Antarctic" size. The table should contain some small proportion of carbonaceous and nonchondritic objects. MORP meteor 223 is believed to have been an iron, judged from its long smooth light curve of modest peak magnitude.

The Type I fireballs in the data from the European Network are not restricted to objects believed to have dropped meteorites. In several cases Ceplecha has specifically stated that no significant terminal mass was to be expected. The data represent, then, the orbits of material of Type I in the atmosphere rather than for surviving meteorites. Since Type I and Type II (carbonaceous) fireballs were not divided into distinct groups without overlap by the criterion used to define the types, some minor admixture of carbonaceous material is to be expected, along with the occasional iron, but the group should be dominated by ordinary chondrites.

The progression in the three plots of Figure 1 may be interpreted as a progression from "definite" meteorites to "highly probable" meteorites to meteoritic fireballs. When we ask about typical orbits for meteorites we must be precise in defining the objects involved. The "meteoritic fireballs" may consist of material identical to known classes of meteorites but the orbits include more high-velocity encounters with the earth, due to larger values of a and i or smaller values of q. If we restrict our attention to those objects which produce meteorites on the

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ground, then the MORP data with its reduced concentration of large values of q and its much smaller group with a <1, relative to the PN meteors, may be typical, whereas the group selected from the PN data is most secure in rejecting doubtful cases. The prevalence of Aten-type orbits in the PN group (11% of those in Figure 1 have a <1) is probably due to the preferential selection of very slow meteors for orbit reduction since they tend to be events with long durations and smooth light curves.

The mean velocities of the three groups of fireballs are 16.4, 18.2 and 24.4 km s^{-1}. Those MORP objects whose main mass is estimated as larger than 1.0 kg have a lower average entry velocity than the entire group, namely 15.0 km s^{-1}. They were also observed to much lower end velocities than smaller objects (6.1 vs 9.5 km s^{-1} for objects less than 1 kg) supporting the belief that the PN group is likely deficient in small meteorites. Depending on unknown details of the proportion of an original meteoroid that survives the atmosphere, as a function of initial velocity, it is quite possible that small meteorites (<1 kg) are, on the average, associated with somewhat faster fireballs than large meteorites. This could add another complication to the problem of defining "typical" orbits For the present, it appears that typical orbits of earth-crossing objects that deposit meteorites are similar to those listed in Table 2, i.e. direct orbits of low inclination, with perihelia generally between Venus and the earth and with aphelia in the asteroid belt.

The authors wish to thank Dr. Zdenek Ceplecha for providing data on some of the EN fireballs prior to publication.

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DISCUSSION

HINDLEY: To what extent are the terminal mass estimates influenced by modelling of the luminous path? How reliable are the masses?

HALLIDAY: Uncertainties in the shape of the body and fragmentation effects could produce errors of a factor of two or larger in the masses.

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