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1. Photographic Fireball Networks

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Three networks for the photography of bright fireballs are now in operation; in the central United States, central Europe and western Canada. A detailed comparison is made of the parameters which describe the three networks. Although only two meteorites for which photographic orbital data is available have been recovered, the networks are contributing valuable data on fireball orbits, influx rates and problems of meteor physics.

A MAJOR DIFFICULTY IN OBSERVATIONAL METEOR ASTRONOMY is the unpredictable nature of the events of interest. The population of observable meteoritic events is defined by the product of the flux of suitable particles, the area of the atmosphere under observation and the duration of observations. Where the flux of suitable meteoroids is reasonably high, as in radar meteor astronomy or direct photography of faint meteors, moderate observing intervals suffice to accumulate considerable data. For bright fireballs, however, the flux is so low that very large areas must be monitored for long intervals to obtain any statistically significant volume of observations.

There are now three networks for fireball photography in operation. Planning for the Prairie Meteorite Network in the central plains of the United States began about a decade ago. The basic aims, principles of operation and instrumentation were described by McCrosky and Boeschenstein (1965). The successful photography of the flight of the Pribram meteorite, using conventional meteor cameras (Ceplecha, 1961), led to the establishment of a network of all-sky cameras in Czechoslovakia for fireball photography (Ceplecha and Rajchl, 1965). This network has since been expanded to include the southern area of Germany and is known as the European Network. During the early stages of operation, a photographic network will bring successive stations into operation gradually and a variety of instrumental problems tends to reduce the efficiency of operation for at least several months, so that it is difficult to define a single date when a network became active. The Prairie Network and the European Network may be considered to have begun operations about 1964 (McCrosky and Ceplecha, 1969).

A third network now operates in western Canada, known as the Meteorite Observation and Recovery Project, or MORP Network. The effective beginning of routine operations for this network may be taken as early in 1971. The MORP network has had an advantage in that it could draw on the early experience of the other networks, although the major decisions on instrumentation were taken in 1966 and 1967 when only quite preliminary results were available from the operation of the first two networks.

NETWORK PARAMETERS

Let us examine the various parameters which describe the design and operation of a meteorite camera network. Each one involves some sort of compromise in its selection and the choices adopted in the three networks now in operation may be compared. Local geographical conditions, distribution of population, the availability of engineering design facilities and of financial support are some of the considerations which influence the decisions. Much of the discussion to follow is summarized in table 1 where each heading below is assigned a row in the table.

Number of Stations and Station Spacing

Calculation of the meteor trajectory requires a minimum of two-station photography but the confidence in the results may be strengthened in some cases if more than two stations observe a meteor. As the anticipated expense of the instrumentation and operation of a typical station gradually increases during the planning stage, there is a temptation to increase the station separation to limit the total number required and hence the total cost. If the camera focal length is large then positional accuracy may be maintained to a greater range from each station, although the danger of one-station observations due to scattered clouds (or instrumental failure) will increase as the station spacing approaches the point where only two stations could provide coverage for a given event. The number of stations in each network is shown in the first row of table 1 while the second row shows a typical separation of any station from an adjacent one. The European Network is characterized by many closely-spaced stations compared to the other two networks.

Figures 1, 2 and 3 are maps of the three networks, drawn to the same scale, showing the location of all stations of the present networks.

Number of Cameras

The Prairie Network employs four wide-angle cameras per station, the European Network has a single all-sky camera, while the MORP stations each have five cameras. A small area near the zenith is obscured by the mounting for the camera itself above the convex mirror in the all-sky version. The other networks cover the sky to altitudes of about 60° but have small gaps in the coverage between adjacent cameras near the horizon.

Focal Length

The three networks differ widely in the focal lengths of their camera systems, as shown in the table. The European Network (effective focal length = 5.7 mm) records the all-sky photographs on 35-mm film, the MORP cameras use 70-mm film, while the much longer focal length of the Prairie Network cameras is used with a 9½-inch (24 cm) film format.

Occulting Rate

The selection of a frequency at which the meteor trail is chopped involves an interesting compromise. A knowledge of the deceleration of the meteoroid in the atmosphere is required to estimate the physical size of the body for the ballistic calculations of the terminal, dark portion of the flight path. The deceleration value will be more secure if it is based on many measures per second, especially since there may be sudden changes in deceleration due to fragmentation of the body.

TABLE 1.—*Comparison of Network Parameters*

Row	Parameter	Prairie	European	MORP
(i)	No. of stations	16	46	12
(ii)	Station spacing, km	250	87	193
(iii)	No. of cameras per station	4	1	5
(iv)	Focal length, mm	152	5.7	50
(v)	Occulting rate, s^{-1}	13.3	12.5	4
(vi)	Dash length, mm	0.236	0.034	0.330
(vii)	Meteor timing	(a) Photometer (b) Shutter code	Visual observers	Photometer
(viii)	Area of atmosphere, km^2	11.4×10^5	10.8×10^5	8.3×10^5
(ix)	Search area, km^2	13.6×10^5	4.4×10^5	7.1×10^5

FIGURE 1.—Map of the Prairie Network showing the location of 16 stations. The curved outline defines the search area as described in the text.

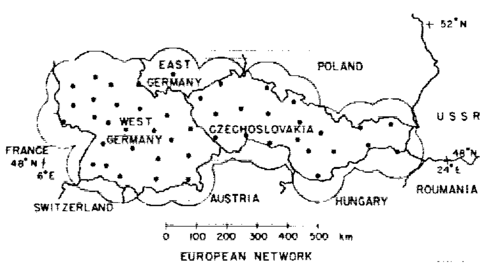

FIGURE 2.—Map of the European Network showing the location of 46 stations and the search area.

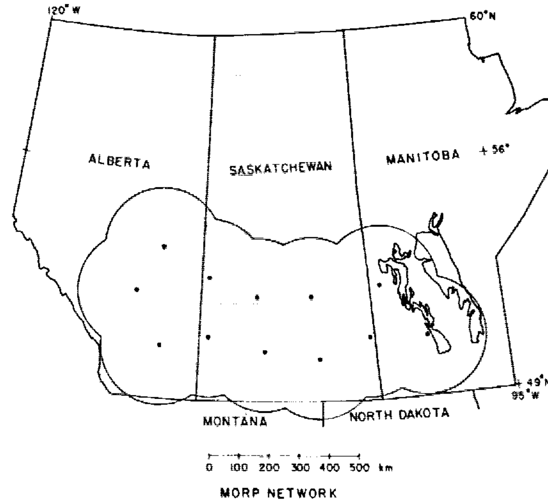

FIGURE 3.—Map of the MORP Network showing the location of 12 stations and the search area.

On the other hand, there is a real danger of overexposure in the important, lower part of the trail, hence if the segments are very short they may blend together. Due to the effects of trailing fragments or persistent luminosity in the wake of the main meteoroid it is common for the beginning (upper) end of each segment to be confused whereas the lower end of the segment is sharp, especially if the occulted interval is relatively long. As a result the best deceleration values may come from restricting the calculations to the lower end of each segment. If the segments are so short that they are measured as separate dots rather than dashes, there is some danger of a progressive shift in their measured positions as the wake effects increase, in the sense of yielding a spuriously large deceleration. If, however, only the lower ends are used, there is a possibility of a spuriously small deceleration while the meteor luminosity is increasing due to a lengthening of each segment from increased exposure effects.

Both the Příbram (Ceplecha, 1961) and the Lost City (McCrosky, 1970) fireballs showed separate fragments in the photographs and such fragmentation is the rule for stone meteorites. It is important to be able to study the individual tracks and to identify recovered meteorite fragments with the corresponding photographic tracks. If the fragments develop an appreciable lateral separation their tracks may be resolved if the orientation is favorable and the range from the station is small or the camera focal length is sufficiently large. If the separation is entirely along the trajectory (and such separations exceeding a kilometer are quite possible) then the visibility of the lesser pieces is improved as the exposure interval becomes a smaller fraction of the complete shutter cycle. For a slow occulting rate a larger separation of fragments is observable before the image of a trailing fragment becomes confused with the preceding image of the leading or main piece.

The MORP cameras have a slow occulting rate in an attempt to realize some of these advantages at the expense of a smaller number of measured points. For the first seven years of its operation the Prairie Network used an occulting rate of 20 breaks per second. Its cameras are controlled by a photometer to reduce the lens opening with a diaphragm and filter if the meteor becomes exceptionally bright, in order to prevent overexposure. The occulter in the MORP system is nearly a focal-plane wheel with three equal segments containing filters of approximate densities 0, 3 and 5, so that the transition from density 3 to 5 may be observable even if both ends of the dense segment are badly overexposed.

Meteor Dash Length

As shown above in considering spurious deceleration effects, the length of a single meteor segment or dash on the film (not including the occulted portion) is of interest. Let us consider the case, which is important for meteorites, of a slow object at a low meteoric height. If we assume the body has been decelerated to 10 km/s then the transverse component will normally be about 8 km/s. For each network take such an object midway between two typical stations at a height of 30 km. The length of one dash will then be as shown in the table. For an actual meteorite fall we can expect the terminal velocity of luminous flight to be even lower by at least a factor of 2 and also the range will normally be greater than assumed above for at least one of the two best photographs. In the Prairie and MORP networks the gap between dashes is twice the length of the dash, in the absence of photographic overexposure effects, so that it is possible to photograph a complete segment of a fragment between the main segments, as shown in figure 4. For the European Network the dashes and the gaps between them are of equal length.

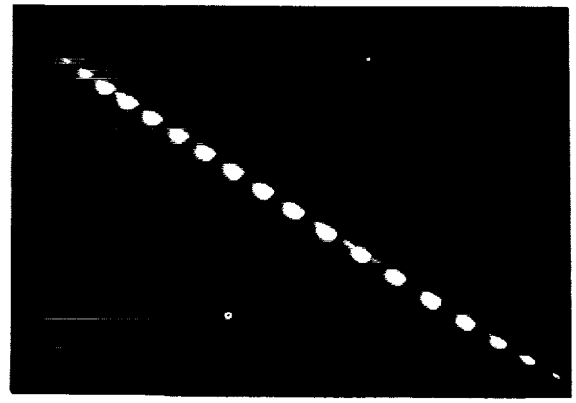

FIGURE 4.—A bright fireball photographed from the MORP station at Watson, Saskatchewan on August 18, 1971. Seven other stations also recorded this event. Note the fragmentation near the bottom of the trail, the bright, decelerating fragment about eight segments before the end and the effects of wake in the upper portion of the trail.

Meteor Timing

Accurate time is required for the reduction of reference points on the star trails, and although the time of appearance of the meteor is not required in the solution for the atmospheric trajectory, it is needed to determine the right ascension of the radiant and the meteor orbit. The Prairie Network uses a signal from a photometer to detect the presence of a bright meteor and, moreover, the occulter is an oscillating blade rather than a rotating disk, which is programmed with an ingenious code so that the omission of certain dashes in the meteor trail defines the time of the meteor to not worse than 5 s. The MORP system employs a meteor detector in which a photometer views the sky through two concentric perforated cones and interprets a flickering signal as a probable meteor. The European Network relies on the high population density within the network to provide a time from visual observations of bright fireballs.

Area of Atmosphere

In calculating the areas covered by the photographic networks it is important to distinguish between the area of the atmosphere effectively surveyed for bright meteors and the area of the Earth's surface over which a meteorite search might be conducted with a reasonable chance of success. The criteria used to define the two cases are rather arbitrary. Both the European and MORP networks are elongated rather than roughly circular, hence the computed areas are quite sensitive to the limit of effective coverage beyond the stations on the perimeter of the network.

Any meteor that drops a meteorite must be quite luminous at an altitude of 60 km. Following McCrosky and Ceplecha (1969) the area of the atmosphere surveyed by a network is taken to be the area for which at least two stations will observe the meteor at an elevation of at least 10° above the horizon when at a height of 60 km. This limit corresponds to a ground distance of 298 km from each station (allowing for Earth curvature) and all three networks should record bright meteors effectively under these conditions. Actually many meteors will be recorded at altitudes below 10° although the Prairie and MORP networks have some gaps between the coverage of adjacent cameras near the horizon. Due to the large spacing between individual stations in the Prairie Network the two-station requirement of the criterion used here greatly restricts the fringe area included in the region just beyond each station on the edge of the network.

Search Area

The effective search area should include the interior area of a network and an external fringe based to some extent on the network's ability to retain positional accuracy comparable to that found in the interior of the network. It should also take some recognition of the suitability of the terrain for a search. The search areas shown in table 1, and indicated on the maps of figures 1 to 3, include all points for which a meteorite fall would be closer to one station of the network than the typical spacing of stations within that network. For the Prairie Network this leads to a larger search area than atmospheric area because of the one-station requirement whereas the MORP and European networks have reduced search areas because of their smaller station spacings. A criterion based on the effective range being proportional to camera focal length might have been considered and would have increased further the effective search area of the Prairie Network relative to the others.

Although at first sight it seems anomalous to include in the search area for the Prairie Network events which were excluded in the atmospheric coverage, the two problems are separate and the anomaly is due more to the strict nature of the elevation criterion than to any likelihood of grossly inadequate observations for the search area. The Prairie Network enjoys a further advantage in that essentially all the search area is suitable for an actual search. In the European Network the search area in table 1 still includes regions of the Alps and Carpathian Mountains in addition to substantial forested areas. The MORP search area includes a narrow fringe of forest on parts of its western and northern boundaries and some large lakes in Manitoba. The lakes, however, offer good conditions for a search during several months per year when they are covered with ice. (Some 13 percent of Canadian meteorites have been recovered from ice surfaces.)

The three networks combined survey 3.0×10^6 km^2 of atmosphere, with a search area estimated at 2.5×10^6 km^2, or 1.7 percent of the land area of the Earth.

NETWORK OPERATION

The routine operation of a meteorite camera network is a large undertaking although we will dismiss it here with only brief attention. All networks use a local operator assigned to each station whose duties include routine checks of the equipment, changing films when necessary and keeping local records. The European Network is directed from Ondřejov Observatory in Czechoslovakia and the Max-Planck Institute für Kernphysik in Heidelberg, Germany. The Prairie Network is directed from the Smithsonian Astrophysical Observatory in Cambridge, Mass. with a field headquarters at Lincoln, Nebraska, while the MORP Network is directed from the National Research Council of Canada, Ottawa, Ontario, with its field headquarters in Saskatoon, Saskatchewan. The operations of film processing, searching, measuring and computer reduction are performed either at the field headquarters or at the main institution headquarters. The operation of a meteorite network presupposes the intention of conducting meteorite searches. The best method of conducting such searches requires some advance planning although these plans may require modification due to the local circumstances of a particular event.

METEORITE INFLUX RATES

In the planning stage of the Prairie Network the expected meteorite fall rate was estimated by McCrosky (McCrosky and Ceplecha, 1969) as 4.5 meteorites/yr, each 1 kg or larger, in an area of 10^6 km^2 during the hours of darkness. This was based on the estimated rates published by Hawkins (1960) rather than those of Brown (1960) which, at this mass limit, would predict only 15 percent as many as Hawkins estimated. McCrosky reduced the estimate of observable falls by a factor of 3 as a generous allowance for poor weather conditions and hence he expected to observe one or two meteorite falls per year in the Prairie Network, which is somewhat larger than 10^6 km^2.

In the six years from 1964 to 1970 the Prairie Network photographed and recovered one meteorite, Lost City (McCrosky, 1970). Four other events are mentioned by McCrosky and Ceplecha (1969) which may have produced meteorites and McCrosky et al. (1971) have described another probable meteoritic event less than a month after Lost City. On this basis it is difficult to justify a rate higher than one observable meteorite fall per year in an area of about 1.4×10^6 km^2. McCrosky and Ceplecha's (1969) data indicate that 46 percent of nighttime hours were usable so that if six meteorites were observed the fall rate may be estimated as high as 4×10^{-10} (km^{2}h)$^{-1}$, during the hours of darkness. The recovery rate, however, based on the Lost City event alone, is about 7×10^{-11}(km^{2}h)$^{-1}$ for clear nighttime hours.

Two other rough calculations of recovery rates of new falls are considered for comparison. Beginning with the Příbram fall in 1959 there appear to be 45 recorded meteorite falls to the end of 1970, of which 11 were in western Europe, south of the Baltic Sea and west of the U.S.S.R. This area of 3.6×10^6 km^2 thus yielded new meteorites at a rate of 3×10^{-11} (km^{2}h)$^{-1}$, a result in general accord with the observational data used by Hawkins. Only one of the 11 meteorites was appreciably smaller than 1 kg in size. Due to incomplete recovery this estimate is obviously a lower limit to the true rate.

In western Canada four fresh chondrites were recovered in that part of Alberta south of latitude 57°N (4.4×10^5 km^2) between 1952 and 1967. In one case (the Vilna meteorite) the mass recovered was less than a gram but there is some reason to believe large pieces may also have fallen. The indicated recovery rate is 6×10^{-11} (km^{2}h)$^{-1}$. All four falls were during clear, dark hours, however, so that if one assumes 50 percent clear weather and an average of 10.5 hr of darkness per day, a nighttime fall rate of 3×10^{-10} (km^{2}h)$^{-1}$ would be obtained, in good agreement with the rate derived if the Prairie Network observes one meteorite fall per year.

Obviously it will require several more years of operation of the networks to yield reliable values of the influx rate of meteorites. With an expectation of about 1800 clear, dark hours per year the three networks combined should attempt 1.8 searches per year if we adopt the search areas of table 1 and an influx rate of 4×10^{-10} (km^{2}h)$^{-1}$ for suitable meteoroids.

STATUS OF THE CAMERA NETWORKS

When the meteorite camera networks were proposed and constructed they were expected to yield at least partial answers to a variety of problems. Since this type of program is definitely a long-term operation it is still premature to assess the performance of the networks but it is of interest to examine some of the original questions in the light of experience gained with the networks.

The Prairie Network soon established that bright fireballs were not as rare as had been expected and McCrosky (1968) studied the orbital characteristics of 100 members of the group. Kresák (1970) has suggested that a scarcity of long-period, high-inclination orbits is at least partially due to the rejection of meteors with durations less than one second rather than to the absence of such meteors among fireballs. The flux of fireballs as a function of their photometric mass has been given by McCrosky and Ceplecha (1969) from Prairie Network data. Further observations are unlikely to alter these distributions substantially except possibly for such factors as corrections for observational selection or the dependence of photometric masses on details of the physical theory of meteors.

In terms of meteorite recoveries from the networks, Lost City is the only success to date and the recovery rate is disappointingly low. Both Pribram and Lost City are bronzite chondrites which constitute the second most common group of meteorites (Millman, 1969). It might be expected that a hypersthene chondrite, the most common type, should be recovered from the networks before long, but for the rarer types such as achondrites, irons, or stony-irons it may well take many years to get a single recovery for even a very few of the dozen types of meteorites in these classes. Orbital data on these rare classes are of great interest, so partial success in providing these data remains a prime goal of the networks.

In the discussion of meteorite influx rates above, the uncertainty in using data from the camera networks was seen to be caused by the difficulty in distinguishing between those events which may have dropped meteorites that remained undiscovered by the search and events which, although equally bright, left no solid pieces of appreciable size. A solution to this problem also has very practical implications in the organization of costly meteorite searches. General criteria for a meteorite fall include low initial and terminal velocities, deep penetration into the atmosphere and the absence of spectacular terminal flares. Levin and Simonenko (1969) suggest that there must be a sharp cut-off near $v_\infty = 20$ to 22 km/s for the upper limit of the velocity at which all but the very largest meteorites can penetrate the atmosphere. If the terminal velocity of the luminous path of a meteor exceeds a value of 8 to 10 km/s then it seems established that the luminosity becomes unobservable because the residual mass is insignificant and, for meteorites of a few kilograms or larger to survive, the luminosity should still be observable at or below 5 km/s. McIntosh (1970) has applied the conventional meteor theory to derive a plot of end-point heights versus surface-to-mass ratios. Even small meteorites should remain luminous to heights of 25 km or lower. Although major atmospheric breakups of meteorites will be marked by bright flares due to the sudden increase in effective area, the light curve of an individual meteorite fragment should decay gradually as the object is decelerated in the late stages of flight. If a spectacular terminal flare is observed, it appears safe to conclude that the meteoroid crumbled completely and no meteorite of a size large enough to warrant a search is to be expected.

When the meteorite resulting from a fireball event is recovered, the density of the object is known and one unknown is removed from the equations for the dynamics of the flight. The dynamical mass, determined from the observed deceleration, still requires some knowledge of the drag coefficient and a shape factor for the meteoroid, whereas the photometric mass depends critically on the luminous efficiency of the ablation process. Considerable progress has been made in experimental determination of the luminous efficiency for artificial meteors (Ayers, McCrosky and Shao, 1970). At low meteoric velocity most of the luminosity is due to iron so the known chemical composition of a recovered meteorite should provide a reasonably good estimate of the luminous efficiency.

Considering the two available test cases, the photometry of Pribram was complicated by overexposure of the photographs but the data appear to require a very massive initial object which suffered repeated fragmentation during its atmospheric flight, with the fragmentation beginning at normal meteor heights. For Lost City (McCrosky et al., 1971) fragmentation was less severe but there is evidence for a significantly flattened shape with drag forces quite different from the usual assumption for a spherical shape. The two smaller fragments of the meteorite appear to have been affected by aerodynamic lift forces during their flight. More test cases are obviously required.

The operation of a photographic fireball network involves various contacts with the local population. Since witnesses of a fireball or of an actual meteorite fall may be able to contribute very valuable information to supplement the instrumental data from the network, it is desirable to promote a good relationship with the public and a considerable effort is devoted to this aspect of the MORP operation. An information booklet on meteorites is available, meteorite displays are arranged, lectures are given to local organizations, newspaper articles on meteorites and the network are encouraged and suspected meteorites are examined for identification. One new meteorite, a 4-kg chondrite which had been found several years previously, was submitted to the MORP headquarters early in 1971 as a result of this publicity.

Viewing the photographic meteorite networks with the knowledge gained to date it may be concluded that although the rate of acquiring orbital and ballistic data on recovered meteorites is lower than had been expected, the meteorite networks are contributing very significant data on the various problems in meteor astronomy.

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