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PHOTOGRAPHIC FIREBALL NETWORKS

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This year is the centennial of the taking of pictures of meteor phenomenon. The first meteor ever photographed (by L. WEINEK in Prague in November 1885) belonged to the meteor Andromedid shower, the famous protrusion of the periodic comet Biela. For the first 50 years, photographic meteor programs gave rather scanty results. The second fifty years started with the Harvard patrol cameras being equipped with rotating shutters for measuring the meteor velocities, and they were operated continuously by F.L. WHIPPLE (1938, 1954) from 1936 to 1951. This was the first classical double-station program for photographing meteors, which gave enough results (144 published meteor trajectories and orbits) for a better understanding of the meteoroids and the atmosphere and their mutual interaction at "cosmic" velocities. The second large program of double-station meteor photography was the program active on a systematic continuous schedule at the Ondrejov Observatory in Czechoslovakia from 1951 to 1977 (CEPLECHA 1957, CEPLECHA et al. 1959). Eight years after the start of this program, a very bright fireball of -19 maximum absolute magnitude was photographed on April 7, 1959. Four meteorites were found near Pribram in Czechoslovakia in an area predicted from the double-station data on the fireball (CEPLECHA, 1961). This first photographing of a meteorite fall gave rise to the idea of systematic observational programs for photographing fireballs and eventually also meteorite fall was photographed, pointed to the fact that many stations over a large area each with cameras covering the whole sky, would be required to graph fireballs and meteorite falls.

Almost simultaneously in the fall of 1963, the first stations of two networks were put into operation, in Czechoslovakia and in the U.S.A. The Czechoslovak network, which later on, after being joined by European countries, became known as the European network, used one all-sky camera operating at each station. The spacing of the stations was 90 km on the average. The equivalent focal length of the stations all-sky camera in the classical mirror arrangement was only 6 mm, but the precision was usually good, because deep penetrating fireballs at heights below 40 km were still rather close to two or three stations. The number of stations operating in Central Europe nowadays is oscillating around 50. During the last 10 years the Czechoslovak part of the Network was modernized by using fish-eye cameras with a focal length of 30 mm. The extremely good optical quality of the Zeiss Distagon objectives enables the derivation of position from one photograph of the whole sky hemisphere (the diameter of the image is 80 mm) with a precision of one minute of arc. The camera is a small handy box (25 x 20 x 20 cm) weighing 4 kg, an instrument prepared for any type of field work and for easy automation. The Czechoslovak part of the Network has the prospect of another decade of operation.

The Prairie Network in the U.S.A. with 250 km spacing between adjacent stations, used 4 cameras with 1552 mm focal length and 90° field of view at each station. The large distances between neighboring stations were very unfavorable for recording trajectories below 40 km. Usually only one station was close to the lower part of the fireball trajectory. The number of stations was 16 and the operation of the Prairie Network terminated in 1975.

In 1971, the Meteorite Observation and Recovery Project known as MORP began routine photographic observations in Canada. Each of 12 stations is equipped with 5 cameras having 50 mm focal length. They record about 100 fireballs per year, for which about 7 drop a total mass of at least 100 grams on the ground. The operation of the MORP Network will terminate this year, but the reduction of the data will continue.

The details on all three fireball networks and references can be found in a survey paper by Halliday (1971). The only change since that time, the use of fish-eye cameras in the Czechoslovak part of the Network, I have already mentioned. The areas covered by the Networks are about a million square kilometers for each. Future programs with automatic fish-eye cameras should cover bigger areas than that.

From all the networks, data on about 700 fireballs are available at the moment. Data on Prairie Network Fireballs were published in survey papers by McCROSKY et al. (1976, 1977). The data on individual European Network Fireballs were published in the Bull. Astron. Inst. Czechosl. and in the SEAN Bulletin. Meteoritics and the Journal of the Royal Astron. Soc. of Canada contain data on some MORP fireballs, but most of the European and Canadian fireball data are available only in the original computer files. Thus data used by other investigators than those directly involved with the observational program were usually the data on the Prairie Network fireballs.

The Prairie Network produced data on on meteorite fall, the Lost City meteorite (McCROSKY et al. 1971). The MORP Network was successful in obtaining data for one meteorite fall, the Innisfree meteorite (HALLIDAY et al. 1978, 1981). Altogether 3 meteorite falls have been photographed globally up to this time.

Except for the hope of repeating the photographic records of a meteorite fall after the Pribram success, the main objective of the networks was aimed at relations of the meteoroids, i.e. bodies before entering the Earth atmosphere, to meteorites, the recovered rests of ablated meteoroids on the ground. At the start of operation of the fireball networks, there were almost no precise data available on bodies with initial masses over 1 kg. The fireball networks gave data on bodies up to 1000 kg with a few cases as high as up to 100 tons. The initial idea was based on speculations that "friable" meteoroids, which were assumed to be cometary in origin, should become an insignificant population among the bigger bodies. If bigger bodies would be mostly solid asteroidal meteoroids, then fireball data might help in calibrating the luminous efficiencies and other quantities in the physical theory of meteors poorly known for smaller bodies. Then the properties by hypothetical cometary material would be better understood. But this proved false just with the first results of the networks. There were more bright fireballs than predicted by simple extrapolation, which simply said that the decrease in numbers slowed down with increasing mass. But there were fewer fireballs penetrating very deeply into the atmosphere or, in another words, less predicted meteorite falls than expected from extrapolations. The problems in connection with searches for small meteorites in predicted areas made the discrepancy between the number of fireballs and of meteorite falls even larger.

The explanation of this situation was found in the existence of different populations of big meteoroids. Even if the whole problem was dealt with by statistical methods, it is useful to visualize the huge difference using individual representatives of various populations as it is shown in Table I. In the Table there are fireballs of approximately the same velocity, the same maximum and integrated brightness, the same inclination of the trajectory to the horizon, but widely differing

Table I. Example of PN-fireballs with comparable velocity, inclination of trajectory and brightness, but with differing terminal heights.

No. of PN-fireball	39276	39406B	40425	39533	39450
V (km/s)	25.8	23.3	25.6	23.5	25.6
M_{max} (absolute magnitude)	-10.6	-10.6	-10.5	-8.6	-11.7
$\log\left(\int_{t_B}^{t_E} I dt\right)$	13.55	13.44	13.79	13.51	14.23
$\cos z_R$	.626	.881	.640	.623	.963
h_E (km)	68.9	57.1	41.7	35.1	32.3
assigned type	IIIB	IIIA	II	I	I

terminal heights. Between the most solid bodies and most friable bodies, the air density at the terminal point of the luminous trajectory differs by a factor of 1000. The classification of fireballs into individual groups is based on such a huge difference of 3 orders in air densities, which represents the combined effect of the different ablation and different bulk density of the meteoroids, and should be connected with different structure andcomposition.

Details on the four different populations of big meteoroids can be found elsewhere (CEPLECHA and McCROSKY 1976, CEPLECHA 1977, CEPLECHA 1985, SEKANINA 1983, WETHERILL and REVELLE 1981 a,b). Four independent methods gave results differing in detail, but the existence of four groups of fireballs according to the various ablation rates of their bodies, as found by CEPLECHA and McCROSKY, had been confirmed. Here I give only a very brief summary of the fireball groups. Group I fireballs have the lowest ablation rate and the greatest bulk density; among them are the Pribram, Lost City and Innisfree meteorite falls. Group I was proposed to be similar to ordinary chondrites. This classification was done before the Innisfree meteorite fall. Group II fireballs belong to meteoroids of somewhat lower density and greater ablation rate than the Group I meteoroids. It is proposed that the Group II fireballs belong to the carbonaceous bodies, which most disintegrate in the atmosphere; only the least friable members of their population can reach the ground as carbonaceous chondrites of CI and CM types. This material may be both of asteroidal and cometary origin, but recent work of WETHERILL and REVELLE (1981b) based on orbital definition of cometary origin, prefers the cometary source. The average ablation coefficient of a type I fireball is 0.014 s^2/km^2, while the value for a type II fireball is 0.042 s^2/km^2 (CEPLECHA, 1983).

Group IIIA contains bodies with a high ablation rate and small bulk density of somewhat less than 1 g/cm^3. The cometary origin of these meteoroids is evident, because cometary shower meteors belong to this group. Also the two systems of orbits i.e. the short-period ecliptically-concentrated system and the long-period randomly-inclined system (IIIA) exist among fireballs of Group IIIA, in complete analogy to cometary orbits.

The fourth group of fireballs is denoted IIIB. Bodies of this group have the highest known ablation rate and the smallest bulk density of a few tenths of g/cm^3. Fireballs of the Draconid meteor shower belong to this group. The cometary origin is also evident. It is surprising that this group contains relatively more bodies among fireballs than among fainter meteors.

We have detailed knowledge of meteorites from laboratory studies but little information of their orbits. The three directly photographed meteorite falls are quite insufficient in this respect. The classification of fireballs by statistical methods applied to the whole bulk of data cannot avoid the problem of a significant statistical ad mixture of no-meteorite fireballs. WETHERILL and REVELLE (1981a) proposed four criteria in answering the more specific question: Which fireballs do belong to meteorites? They found 27 Prairie Network fireballs comparable to or greater than Lost City in bulk strength and density. Most of them should be ordinary chondrites. Thus the statistics of orbits of ordinary chondrites increased by one order of magnitude. The orbits are ecliptically concentrated: the highest inclination found was 38°, but the majority of them have inclinations of less than 10°. There perihelia exhibit a concentration close to 1 A.U. in accordance with a previous study of WETHERILL (1969) based on the time-of-fall and radiant distribution of meteorites from visual observations. Semimajor axes spread over a wide range, but some indication of clustering around 1, 2 and 2.5 A.U. is in evidence. The largest semimajor axes are 2.56 A.U. (The value of 4.2 A.U. for PN39057 comes from a wrong value of initial velocity). Aphelia of 4 A.U. are quite frequent, and Pribram is not an exception in this respect as well as in respect to the other orbital elements.

Recently WETHERILL (1985) presented a theoretical model of the orbital evolution of ordinary chondrites, assuming that they are injected with rather small velocities into the 3:1 Kirkwood gap at 2.50 A.U. He assumed that such bodies can become Earth-crossing on a time scale of a million years, as a result of being injected in the chaotic zone discovered by WISDOM (1983) in connection with the 3:1 resonance. The computed distribution closely matches the distribution of orbits of ordinary chondrites derived from Prairie Network observations. Also the predicted fluxes of meteoroids and the time scales are in agreement. WETHERILL proposes as a source of the majority of the ordinary chondrites surfaces of S asteroids in this very limited region of the asteroidal belt, where the largest bodies are 11 Parthenope, 17 Thetis and 29 Amphitrite.

Recently HALLIDAY et al. (1984) published a study of the frequency of small meteorite falls on the Earth's surface based on the Canadian MORP data. They used the dynamically determined terminal masses and found 43 events in 9 years of continuous operation of the MORP network (29 percent of the night hours with clear sky) they have dropped meteorites from 0.1 to 12 kg. They use a previous study of HALLIDAY et al. (1982) on relative variations of meteorite falls for corrections and they gave the flux per year and per million square kilometers as $\log N = - 0.689 \log m + 2.967$, where N is the number of events exceeding m grams. This is the first time instrumental data have been used for deriving the influx rate of meteorites on the Earth's surface. The authors then used REVELLE's (1979) theoretical work and converted the fluxes to masses of pre-atmospheric meteoroids. The result agrees in population index with the previous result of McCROSKY and CEPLECHA (1969) on PN fireballs, but the MORP distribution line for pre-atmospheric masses is lower by 0.94 in log N. The PN data contain all fireballs in contrast to meteorite dropping fireballs selected from the MORP data. This makes about about a factor of 3 and the remaining factor of 3 is presumably accounted for by the low value of the luminous efficiency used in the PN reductions, which led to an overestimate of the masses (REVELLE, 1980). WETHERILL (1985) used the results of HALLIDAY et. al. (1984) and computed the annual flux over the entire Earth in the mass range from 14 g to 140 kg as 3.9×10^4 kg on the surface. This corresponds to a pre-atmospheric mass range from 100 g to 1000 ky, if we assume a typical initial velocity of 14 km/s and an ablation coefficient 0.02 s^2/km^2. The total pre-atmospheric flux of ordinary chondrites inside this mass range before entering the atmosphere and counted over the entire Earth per year is 2.8×10^5 kg.

The interaction of the atmosphere with a big body is still quite regularly described by equations of the so called "single body theory", even if sometimes a rather modified version (REVELLE 1979; BRONSHTEN 1980). The problem of fragmentation of big bodies is quite serious for strong chondritic material penetrating deep into the atmosphere and this problem is decisive for understanding the motion and luminosity of IIIA and IIIB types of fireballs high in the atmosphere. The problem of luminous efficiency leading to overestimates of photometrically derived masses has already been successfully dealt with by REVELLE (1980). On the other hand, the proposed mechanism calls for strong continuum radiation at smaller velocities, which was not observed in spectral records of fireballs down to a height of 30 km and velocity of 7 km/s.

Table II

type	Ceplecha (1977,1983)		ReVelle (1983)	
	density	ablation coeff.	density	ablation coeff.
	g/cm^3	s^2/km^2	g/cm^3	s^2/km^2
I	3.7	0.014	3.7	0.020
II	2.1	0.042	1.9	0.040
IIIA	0.6	0.13	0.9	0.08
IIIB	0.2	0.20	0.34	0.22

Recently REVELLE (1983) also accounted for the different hypothetical porosity of meteoroids of different types. The schematic model, which applied to PN fireballs, yielded values of ablation coefficients close to those values previously from a simpler model by CEPLECHA (1977, 1983), but the bulk densities for type II and especially for types III resulted in somewhat bigger values. (Tab. II).

Basic dynamical data derived from fireball photographs consists of distances along the trajectory, l (obs.), and heights, h (obs.), measured at each shutter time-mark, t. Due to lack of knowledge of the relation l = l (t), even in the scope of single body theory, only least-squares fits of l(obs) and h(obs) were usually done by interpolation formulae. Also, the "observed" velocities, v(obs), were derived from numerical differentiation of l(obs) and the fit was done using a theoretical formula v = v(h). PECINA and CEPLECHA (1983, 1984) derived a new integral l = l(t) in a closed analytic form. This formulation, when applied to PN fireballs, gave much more precise values of initial velocity and ablation coefficient than those published before, when the simple interpolation formula was used. The inherent precision of the PN-fireballs (McCROSKY, 1971 and 1984) is significantly higher (up to one order) than the published solutions (McCROSKY et al. 1977) that have been obtained by means of the interpolation formula. Moreover, the new analytical solution l = l(t) can be used for the entire, rather long trajectory of a fireball with one constant ablation coefficient (the total ablation coefficient). Fireballs penetrating deep into the atmosphere are usually photographed also after they reach the point of maximum deceleration. Significant terminal mass is typical for such cases. The velocity and deceleration at the terminal point of the luminous trajectory of such a fireball is necessary for determining the meteorite search area. The interpolation formula used for the extrapolation below the maximum deceleration point gives an unrealistically higher value of deceleration and a lower value of velocity.

The problem of predicting an impact point for a meteorite fall from its photographic fireball data arose first with the Pribram meteorite fall. The luminous trajectory terminates due to insufficient heat influx, when the velocity becomes too small (about 3 km/s). After the terminal point, the body moves without ablation in a dark-flight trajectory. The motions of a body with constant mass in a resisting medium, the density distribution of which is known, is a classical problem. The numerical computations in a realistic atmosphere depend on the observed terminal velocity and deceleration, on the air density profile, and on the wind field. A knowledge of the mass of the body is not necessary. Also the unknown shape of the body enters only into the assumption of the relative change of the drag coefficient with decreasing velocity. Of course, exotic shapes may give enormous lift forces to the body and then any prediction of an impact point is necessarily fictive. The Pribram, Lost City and Innisfree experiences indicate a precision of better than 1 km for such predictions, if the dark-flight of a meteorite mass of several kilograms is computed. In any case, the method of PECINA and CEPLECHA (1983, 1984) yields more precise valued of velocity and deceleration at the terminal point as derived from the photographic observations of fireballs, and these values are necessary for the predictions of meteorite impact point and impact area.

The greatest trouble in this business is the meteorite search itself. The actual conditions of the countryside inside the predicted search area may be very diverse. Usually at least part of the land is unfavorable for finding anything at all! The search method simply requires looking; it does not matter if one is walking, driving, flying or snowmotoring. To search for bodies of a few hundred grams is almost hopeless, but a few kilogram meteorite fresh fallen on the smooth surface of a spring field can be recovered almost with certainty. The number of searches done in all three fireball networks is close to 50. With 3 meteorites found so far, you need searches for about 15 different meteorite fireballs to recover something. Anybody in a search group should accept the fact that the probability of recovering a meteorite is less than 1 percent for one searcher after spending two or three weeks of intense work in the predicted area of fall.

From the recent study of HALLIDAY et al. (1984), it is also possible to estimate how many searches were necessary on an average to recover each of the two photographic meteorites with well determined terminal masses during the whole operation of all three networks. Innisfree needed about 12 searches for bodies with computed terminal mass of 5 kg and bigger, while the Lost City meteorite need about 6 searches for bodies of computed terminal mass of 20 kg and bigger. During the whole operation of all three networks, only searches for bodies with computed terminal mass of 200 kg or bigger (they never occurred) would yield an almost certain meteorite recovery. It is clear that the actual meteorite search is the weakest point in acquiring photographic data on recovered meteorites.

The initial interest and enthusiasm in big meteoroid studies and in the operation of photographic fireball networks has diminished during the last few years. But still more theoretical studies of the interaction of big meteoroids with the atmosphere as well as more systematic observations of fireballs are needed to solve definitely the questions of the relationship between meteorites and meteoroids before atmospheric entry. Activity in this field is now going on in USSR and in Czechoslovakia. The possibility of continuing this work and creating new interests and methods has been increased by plans for multilateral cooperation between the socialist countries, where this topic should be studied at least during the next five year period.

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