OBSERVATIONAL AND THEORETICAL ASPECTS OF FIREBALLS*

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Abstract. Recent theoretical concepts of large meteoroid entry into the atmosphere are compared and an evident lack of a theory applicable to all observed fireballs is found. A new empirical criterion separating different fireball groups according to structure and composition of their bodies and containing only values directly obtained by photographic observations is proposed. The complex semi-empirical approach is found to be the best approximation to reality we can achieve for all fireballs at the moment. The interpretation of the fireball differences assuming variations in structure and composition of their bodies is the most natural explanation of the observational facts.

The recent success of the Canadian network in photographing the Innisfree meteorite fall (Halliday et al. 1978) added new observational data to be compared with theoretical concepts of atmospheric entry of large meteoroids. Different fragments of the Innisfree meteorite were photographed in flight and the data are rather complete; in any case they are the best from the three meteorite falls photographed so far. The recovered meteorites represent almost all the mass landed. This is reasonably well guaranteed since the trajectory was steep enough to compute a relatively small impact area to be searched for meteorites and several fragments were assigned to individual photographed trails with reasonable certainty. Preliminary data for the Innisfree fireball were sent to me by Halliday.

ReVelle (1976,1978,1979a) and ReVelle and Rajan (1979) published a new quasi-simple ablation model of large meteoroid entry into the atmosphere considering radiative and convective heat-transfer, proposed a new luminosity equation and constructed a predictive pattern of macroscopic and integral luminous efficiency. The model was applied to data on all three photographic meteorite falls with complete success and the initial masses that resulted were about 5 to 10 times smaller than previously derived from the light curves by means of the conventional luminosity equation. Also the terminal masses correspond well to the

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total masses of the recovered meteorites. Moreover, these results are in good agreement with the initial dimensions of the bodies as estimated by counting cosmic ray tracks. Thus ReVelle's theory is found to be capable of explaining the fireball phenomenon for bodies similar to ordinary chondrites. But the theory in its present form seems not to be applicable to fireballs with extremely high terminal heights (type IIIA and IIIB), which comprise about one third of all photographed fireballs. The luminous efficiencies obtained for these fireballs exceed 100% of the kinetic energy.

Table 0. 1971 Theory

Single-body	Baldwin, Schaeffer (1971)
a starting point for everybody	a schematic break-up introduced into the theory with drag-coefficient and heat-coefficient as functions of time
	fits values for the P/N fireballs worse than the single-body theory with constant coefficients

Very recently Padevět (1979) finished comparison of his theory of dynamically significant coma (1977) with the data on PN-fireballs. His theory is applicable to all types of fireballs. The luminous efficiencies are nearly independent of the fireball type within 0.03% and 2% and they correspond to the values given by McCrosky (Ceplecha and McCrosky 1976). The initial masses are of the same order as the photometric masses from the conventional luminosity equation in contradiction with the results from counting cosmic ray tracks. The theory pays a price for giving reasonable luminous efficiencies for all fireballs: the computed terminal masses are about one order larger than the recovered masses of the meteorites photographed. There is some hope of avoiding at least part of this discrepancy by theoretically considering the observed fragmentation into comparable pieces, which has not been done yet.

Comparing both theoretical concepts (Table 1) as they appear after being applied to PN-fireballs, ReVelle's theory is distinctly better off, when deep penetrating fireballs are considered and Padevět's theory seems to work well for the fireballs with high terminal heights, indicating their loose structure. If we are quite strict and consider all the discrepancies, we have only ReVelle's theory applicable to objects similar to ordinary chondrites (deep penetrating fireballs). Fireballs with extremely high terminal heights (type IIIA and IIIB) are far from being fully explained by any existing theory, unless we allow extremely high ablation coefficients and extremely low densities for these meteoroids.

Ceplecha and McCrosky (1976) published a thorough study of fireball terminal heights, found four statistical groups and interpreted them in terms of differing composition and structure of the meteoroids. Ceplecha (1977) combined these results with older analyses of fainter photographic meteors and constructed one coherent pattern. All these

Table 1. Recent Theoretical Concepts of Fireballs

<table>
<tr><th>ReVelle (1976)</th><th>ReVelle, Rajan (1979)</th><th>Padevĕt (1977)</th></tr>
<tr><td>radiative and convective heat-transfer changing the coefficients of "single body" theory with time</td><td>conventional luminosity equation corrected for energy transferred to the air</td><td>"dynamically significant coma": radiative and convective heat-transfer, cross-section of the body corrected for the dynamics of the ablated material. conventional luminosity equation</td></tr>
<tr><td colspan="2">applicable to type I fireballs (possibly to type II if appropriate corrections for fragmentation processes were included)
not applicable to type IIIA and IIIB (one third of all fireballs)</td><td>applicable to all types of fireballs</td></tr>
<tr><td colspan="2">luminous efficiencies for IIIA and IIIB fireballs are physically unrealistic (more than 100% of kinetic energy)</td><td>luminous efficiencies for all types of fireballs are between 0.03% and 2%, independent of the fireball type and corresponding to the values used by McCrosky</td></tr>
<tr><td colspan="2">initial masses are one order less than photometric masses from conventional equation and approach dynamic masses for type I and type II fireballs</td><td>initial masses are of the same order or larger than photometric masses from conventional equation and approach the values of computed dynamic masses for all types of fireballs</td></tr>
<tr><td colspan="2">terminal masses for photographed meteorite falls agree with the masses of the recovered meteorites</td><td>terminal masses for photographed meteorite falls are one order larger than masses of the recovered meteorites (This discrepancy may vanish if appropriate corrections for fragmentation processes were included)</td></tr>
<tr><td colspan="2">author assumes the discrepancies for IIIA and IIIB fireballs could be explained by more ablation and/or fragmentation if a "non-single body" approach were adopted without assuming extremely low meteoroid densities</td><td>the theory explains different fireball types by different structures of the material with densities varying only between those of ordinary and carbonaceous chondrites</td></tr>
<tr><td colspan="2">the masses derived from this theory agree with the dimensions of the bodies derived from counts of cosmic ray tracks</td><td>conflicts with the dimensions of the meteorites derived from counts of cosmic ray tracks</td></tr>
</table>

results were dependent on calibration by the Lost City fireball. The Innisfree fireball gives a new opportunity for an additional check. The data on Innisfree were analyzed in the same way as Ceplecha and McCrosky (1976) studied the PN-fireballs. The resulting

$SD = \log\ (\sigma \Gamma A \rho_m^{-2/3}) = 11.61$ (in c.g.s.) is not far from the Lost City value of -11.77. If a new calibration is based on an average from the values for Lost City and Innisfree, the following values are obtained:

	log σ c.g.s.	log $\Gamma A \rho_m^{-2/3}$ c.g.s.	m_E kg	PE
Lost City	-11.49	-0.28	25	-4.44
Innisfree	-11.41	-0.20	5	-4.45

(σ is the ablation coefficient, $\Gamma A \rho_m^{-2/3}$ the shape - density coefficient and m_E the terminal mass). This is a perfect confirmation of the old calibration, which improves the old theoretical value of $m_E = 45$ kg for Lost City which was considered somewhat greater than the real terminal mass. The PE values are almost identical for both fireballs: they both belong to group I. The new calibration has changed nothing in the delineation of the groups. Of course, fireballs close to the assumed boundary lines may belong to neighboring groups: the separation has only statistical meaning and the overlaps of wings of the distributions, partly caused by observational errors, prevent the classification of individual cases with full certainty.

Wetherill, ReVelle and Rajan recently (1978) proposed a new method for studying the differences in terminal heights (Table 2). They computed dynamic masses from the drag equation of the single-body theory with the same constant coefficients for all PN-fireballs. They plotted the initial dynamic masses against end heights scaled according to ReVelle's theory. This analysis contained only fireballs with low terminal heights (the purpose was to identify meteorite-type fireballs). The authors found similar groups to groups I and II of Ceplecha and McCrosky, but the grouping was not identical when individual fireballs were considered. The reason for these differences is evident from the comparison of both concepts in Table 2.

ReVelle (1979b) recently sent me more values of initial dynamic masses of the PN-fireballs. If one computes the initial kinetic energy E_K from these masses and compares it with the total energy radiated in the panchromatic pass-band (Figure 1), the groups are statistically separated, but with a larger overlap than was the case in Ceplecha and McCrosky's analysis. The big spread is mainly caused by making use of observed decelerations without considering their observational errors. Some of the dynamic masses (and thus the kinetic energies) are quite fictitious values. If the standard deviation were one third of the computed deceleration or bigger, the standard deviation of the computed dynamic mass would equal or exceed the value itself. Thus only decelerations with standard deviations much smaller than one third of the deceleration value should be used for the mass computations. Moreover a cautious statistical weighting of individual values according to their standard deviations is necessary, when the initial dynamic mass is computed, but ReVelle took all the decelerations with equal weights

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Table 2. Relation of fireballs to meteorites. Analyses of terminal heights.

	Wetherill ReVelle, Rajan (1978)	Ceplecha, McCrosky (1976)	Ceplecha (new approach, this paper)
initial mass	dynamic (drag equation)	Photometric (luminosity equation)	not used
luminous efficiency	not used	function of velocity based on experimental data	not used
ablation coefficient	$0.2\ s^2 km^{-2}$	individually computed from observed values by six independent methods; does not depend on the scale of the photometric mass	not used
shape-density coefficient $\Gamma A \rho_m^{-23}$	$\Gamma = 1.21$ $A = 0.92$ $\rho_m = 3.7$	individually computed from observed values by 27 independent methods; proportional to cube root of the scale of the photometric mass (or to $\tau^{-1/3}$).	not used
terminal height h_E	observed or where the velocity decreased to 6 km/s	observed (last detected light)	observed
meteoroid densities ρ_m	assumed: $3.7 gcm^{-3}$ resulted: scaling the terminal heights by applying ReVelle's theory to Lost City and Innisfree, most of the fireballs belong to the $3.7 gcm^{-3}$ group, but a secondary maximum may be attributed to bodies with carbonaceous densities (type IIIA and IIIB were not contained among fireballs studied)	from multiple statistical distribution of $SD = \log(\sigma \Gamma A \rho_m^{-2/3})$ calibrated by Lost City and Pribram (zero point) and from scaling σ and $\Gamma A \rho_m^{-2/3}$ on assumption of equal weights, when observational errors were distributed to both these values. SD does not depend on dv/dt.	from multiple statistical distribution of empirical criterion AL, containing only values directly derived from photographic observations (terminal height, inclination of the trajectory, total light radiated in panchromatic pass-band)

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Table 2. (Cont'd.)

	Wetherill ReVelle, Rajan (1978)	Ceplecha, McCrosky (1976)	Ceplecha (new approach, this paper)
PE		simple criterion demonstrated to be statistically equivalent to the values of SD, but with the advantage of handling cases with bad dynamic data (most fireballs lack enough precision to determine SD)	criterion AL is statistically equivalent to PE
character of the method	one-sided by not considering the luminosity data; but calibrated by photographed meteorite falls	both dynamic and photometric data considered; one-sided by assuming the photometric mass is close to real mass, but calibrated by dynamic and photometric data of the photographed meteorite falls	empirical method (exponents chosen to make AL statistically independent of velocity and $\int I dt$; calibrated by Pribram, Lost City and Innisfree)
results	two groups differing in terminal heights, but the analysis is not complete (the extremely high terminal heights were not included; they belong to fireballs with poor dynamic data).	four groups with different terminal heights were found.	four groups with different terminal heights were found and they are statistically equivalent to groups found by means of SD and PE

regardless of their precision. Figure 1 also shows clearly that dynamic masses give rather high luminous efficiencies: we can accept them for group I fireballs, we should be suspicious of the several times 10% necessary for the group II fireballs, but there is no way to explain more than 100% luminous efficiencies for the IIIA and IIIB fireballs except that the dynamic masses are false.

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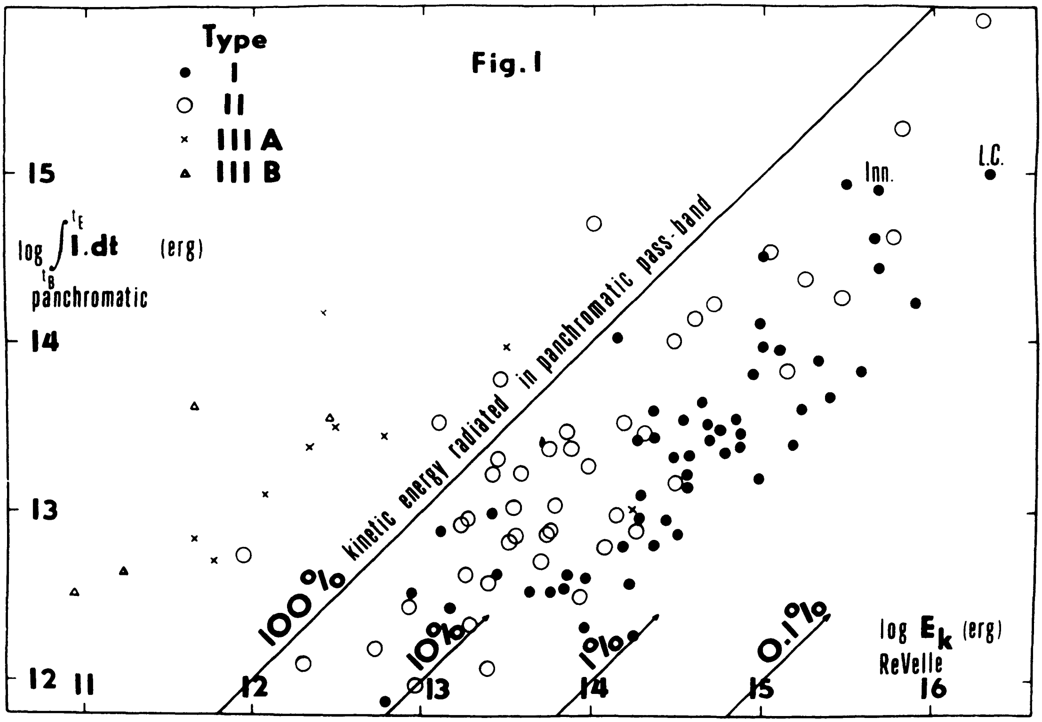
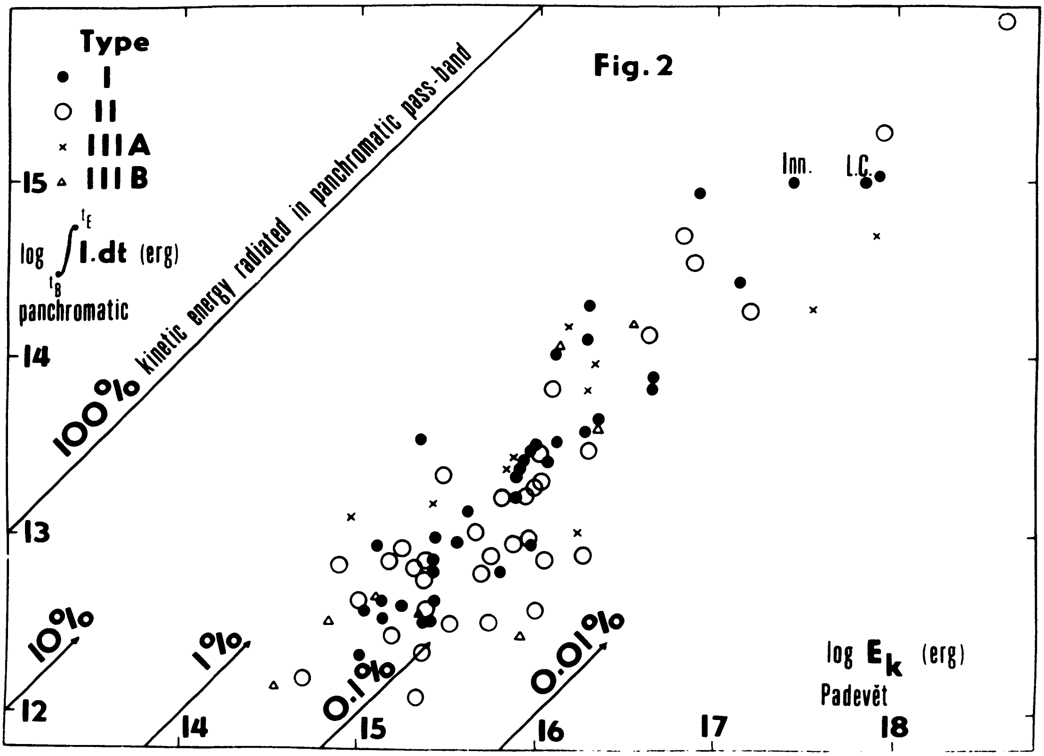


Fig. 1 and 2: The total energy radiated in the panchromatic pass-band $\int_{t_B}^{t_E} I dt$ is plotted against the initial kinetic energy E_K computed from initial masses of ReVelle (1979) in Fig. 1 and from initial masses of Padevět (1979) in Fig. 2. Different types of fireballs according to Ceplecha and McCrosky (1976) are distinguished by various symbols. The straight lines with 45° slope define the same integral luminous efficiency in the panchromatic pass band. L.C. the Lost City fireball, Inn. the Innisfree fireball.

Comparing both methods of statistical analysis of terminal heights of fireballs in Table 2, we can say that the method of Wetherill, ReVelle and Rajan (1978) is one-sided by not considering the luminosity data at all and the method of Ceplecha and McCrosky (1976) is one-sided by assuming the photometric mass to be close to the real mass. Figure 1, speaks for considering both dynamic and photometric data when the terminal heights are analysed. Thus the greater complexity of the method of Ceplecha and McCrosky gave better separation of groups, even if the results are statistically identical in both cases.

The ratio of the dynamic mass computed by ReVelle to the photometric mass computed by McCrosky is in statistical relation to the PE criterion



and to the SD criterion used by Ceplecha and McCrosky in studying the groups of fireballs. Thus both criteria can be considered as expressing the discrepancy between the photometric and dynamic masses and the classification is based indirectly on these differences. The higher the trajectory terminates, the greater the discrepancy between photometric and dynamic mass and the classification moves from I to III B.

An analogous plot to Figure 1 can be plotted in Figure 2 for the masses of fireballs recently derived by Padevět (1979). The statistical groups of fireballs are not evident in Figure 2. The luminous efficiencies are reasonably small and in agreement with the values given by McCrosky. If the fireballs cannot be classified according to this theory using different luminous efficiencies, what is then the meaning of the substantially different terminal heights? When Padevět plotted the PE criterion against $\sigma\Gamma$ computed from his theory, the same grouping resulted as that found by Ceplecha and McCrosky (1976). The groups seem to differ in σ without much difference in the density of the meteoroids. The groups have additional characteristics within Padevět's theory: Group I contains bodies which still continue to emit light after they pass the maximum of dynamic pressure. Groups IIIA and IIIB contain bodies which terminate their luminous trajectories long before maximum dynamic pressure could be reached. Group II contains bodies which approximately reach maximum dynamic pressure at the observed terminal point of the luminous trajectory. In all computed cases the absolute values of these pressures lay between the mechanical strength of ordinary chondrites and carbonaceous chondrites. Thus the explanation of the groups differs from that of Ceplecha and McCrosky and the clue may lie in the structure of the bodies: the IIIA and IIIB bodies terminate their luminous trajectories by sudden complete desintegration of rather large masses.

There are fundamental difficulties in computing the decelerations from fireball photographs. We measure the distances on films and decelerations are their second derivatives. The light image of the fireball could be slightly distorted or small fragments can change the shape of the image and the deceleration starts to have only a local meaning. Any method which avoids the direct use of fireball decelerations is preferable. The criteria PE and SD do not need deceleration for computing their values. The case of the empirical PE is clear: dv/dt is not contained in the definition. The SD case comes out of two expressions of the single-body theory, which I write here without correction terms for the terminal mass:

$$\sigma = \frac{I}{v \left|\frac{dv}{dt}\right| \int_t^{t_E} I dt} \qquad (1)$$

$$\Gamma A \rho_m^{-2/3} \tau^{1/3} = \frac{2^{1/3} \left|\frac{dv}{dt}\right| (\int I dt)^{1/3}}{\rho v^{8/3}} \qquad (2)$$

Because SD is defined as SD = $\log(\sigma \Gamma A \rho_m^{-2/3})$, multiplication of (1) by (2) shows that SD is independent of dv/dt and depends only on $\tau^{-1/3}$. Thus if the observed deceleration is completely false, σ and $\Gamma A \rho_m^{-2/3} \tau^{1/3}$ cannot be determined separately, but SD can still be realistically computed. This was explained previously (Ceplecha (1975), when the impact of observational errors on the resulting σ, and $\Gamma A \rho_m^{-2/3}$ was studied, with the result that SD = $\log(\sigma \Gamma A \rho_m^{-2/3})$ has much smaller error than the values separately. SD and PE were applied to PN-observations by Ceplecha and McCrosky (1976), when fireball groups were studied and delineated.

The use of photometric masses for different criteria separating different fireball groups was questioned by several investigators. This led me to propose a new criterion, which would depend only on values directly accessible to photographic observations. The criterion contains the initial velocity v_∞, the total light radiated in the panchromatic pass-band $\int_{t_B}^{t_E} I dt$ and the total air mass per 1 cm^2, which is penetrated by the meteoroid $\int_B^E \rho \, d\ell$. If we assume a constant air gradient <u>b</u>, the air density $\rho = \rho_0 \exp(-bh)$ can be substituted into the last integral, and changing the variable ℓ from $dh/d\ell = -\cos z_R$ where z_R is the zenith distance of the radiant, and neglecting ρ_B as relatively small compared to ρ_E, we have

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$$\int_B^E \rho \, dl \doteq \frac{\rho_E}{b \cos z_R} \tag{3}$$

A simple exponential relation was assumed to be capable of expressing the ratio of kinetic energy to the radiated energy. The exponents (coefficients in the logarithmic form) were determined from all PN-fireballs so that the criterion does not statistically depend on any of the values defining it. The resulting definition of such a criterion, denoted AL (ablation - light), is:

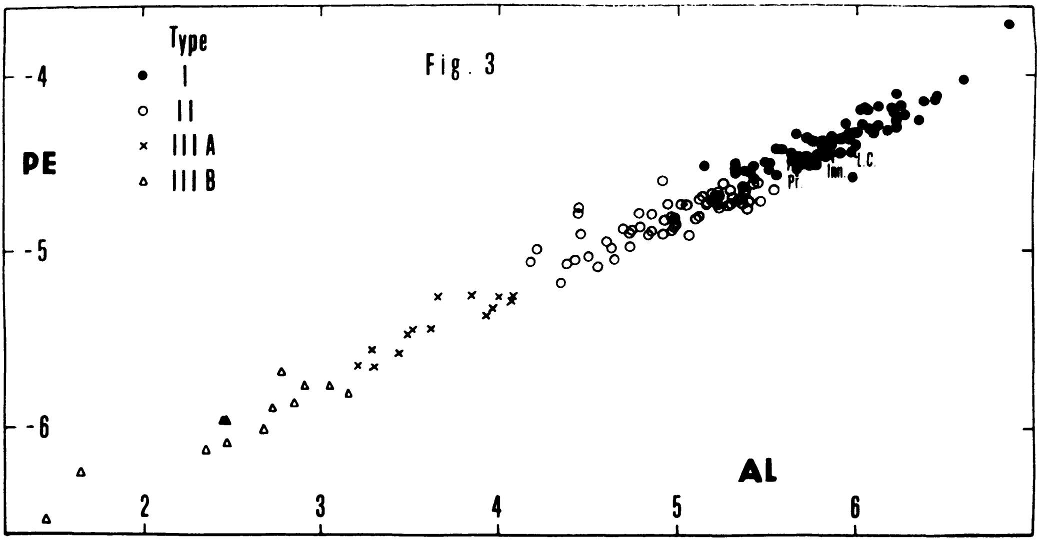
$$AL = 5 \log v_\infty + 2 \log (\rho_E / \cos z_R) - 0.83 \log \left(\int_{t_B}^{t_E} I dt \right) \tag{4}$$

This criterion does not contain the photometric mass and contains only values directly accessible to photographic observations.

If this AL-criterion is applied to the PN-fireballs, the results are statistically equivalent to previous results using the SD and PE criteria. Figure 3 and Figure 4 present the plot of AL against PE and SD, respectively. AL was computed with v_∞ in km/s, with ρ_E in g/m^3 and with $\int Idt$ in 0^m and c.g.s. The photometric mass applied for computation of SD and PE did not cause any significant difference in their statistics, when compared with AL statistics. Of course individual cases close to the boundaries differ, when classified by AL, but this occurs in less than 10% of cases. The general features of the previous classification remain unchanged. Four discrete levels with higher statistical concentration of AL (i.e. of scaled terminal heights) are distinct. The lowest, level I, contains all three photographed fireballs (AL of Příbram is 5.63, of Lost City 5.96 and of Innisfree 5.84) and it evidently corresponds to ordinary chondrites. If fireballs of the same initial velocity and angle of incidence and with identical total energy radiated in the panchromatic pass-band are compared, these levels differ by 8 km from level I to level II, by 18 km from level I to level IIIA and by 29 km from level I to level IIIB.

These differences in heights can also be demonstrated directly by choosing suitable fireballs of approximately the same initial velocity, maximum brightness, total radiated energy and angle of incidence as is given for several PN-fireballs in Table 3. The only value which differs appreciably among the fireballs in Table 3, is the terminal height h_E. The explanation of these big differences by differing composition and structure of the fireball bodies seems to be quite reasonable. In any case, if this explanation should fail, another reason must be found to explain why these bodies with almost identical parameters terminate at air densities which differ by a factor of 1000.

The two theoretical models considered in some detail in this paper are not applicable to all fireballs. Bodies with extremely high or low terminal heights do not fit one or the other theory. The application of these theories to observations have to be calibrated by photographic



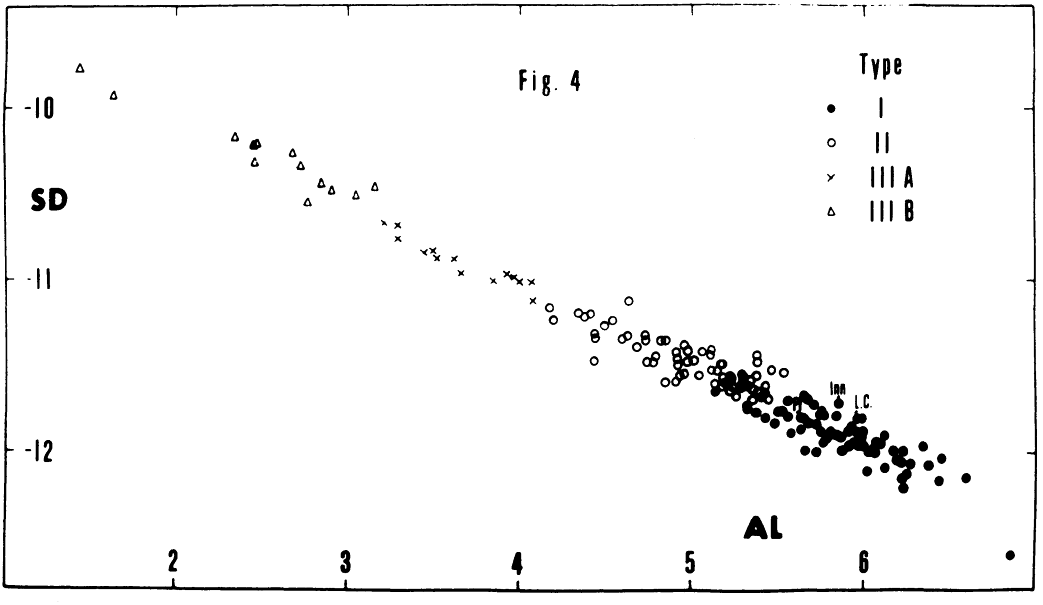


Fig. 3 and 4: PE and SD fireball criteria as defined by Ceplecha and McCrosky (1976) are plotted against a new criterion AL defined in this paper by means of values directly accessible to photographic observations. Different types of fireballs are distinguished by various symbols. Both criteria are statistically equivalent. Pr. the Příbram fireball, L.C. the Lost City fireball, Inn. the Innisfree fireball.

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Table 3. 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
$\log(\int_{t_B}^{t_E} I dt)$	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

meteorite falls. We are far from having any physical theory of atmospheric entry of big bodies which would hold for all fireballs. The complex semi-empirical approach based on the single body theory, but calibrated by photographic meteorite falls and taking into account differences in beginning heights and in orbits and accounting also for observational errors, is perhaps the best approximation to reality we can achieve for all fireballs at the moment. Further theoretical studies are urgently needed to improve this situation. Until then, I would consider that the best explanation of the observational facts is one which postulates differences in structure and composition of the bodies which produce fireballs.

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DISCUSSION

Brownlee: Is there an estimate for the classification of Revelstoke?
Millman: In the 1977 appendix to the catalogue of meteorites in the British Museum (Hutchison, Bevan, Hall) Revelstoke is listed as "Carbonaceous chondrite (Type 1)".

Lokanadham: What is the reason for the poor recovery rates of meteorites from fireball networks?
Millman: A poor recovery rate results from the difficulty in finding a meteorite that has fallen in rough terrain, even if the general area of the fall is fairly well known; and from the fact that many meteoroids that produce very luminous fireballs disintegrate into dust high in the atmosphere.

Hawkes: Have systematic spectral differences been observed between Ceplecha's different classes of fireballs?
Millman: At present there are not enough spectral observations of very bright fireballs to answer this question. For example, no spectrographic data exist for the fireballs photographed on the Prairie Network in the USA, or on the Canadian MORP network.

Hughes: What do you think the effect of including the infrared contribution would be to your $\int I dt$ value?
Millman: There are strong multiplets of O, N and Ca in the near infrared of most meteor spectra but good photometric measures have not yet been made in the wavelength region from 7000 to 9000 Å.

ReVelle: I would just like to say that the dynamic mass considered is ∿3 to 4 times smaller than the "true" mass calculated using ReVelle's model as plotted in Figure 1 (which is incorporated into the initial kinetic energy of the meteoroids). This has the effect of reducing the luminous efficiency of the proposed Group I fireballs to ∿1%, with similar changes for the other two groups. This does not remove the discrepancy for the Group III fireballs but will reduce considerably the luminous efficiencies shown (of order unity).