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**COMPARISON OF FILTER WITH
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DATA**

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COMPARISON OF FILTER WITH PRAIRIE AND EUROPEAN NETWORK DATA

Gregory H. Canavan

Prairie and European Network observations of entry are used in a filter model of fragmentation to produce predicted masses that are compared with the data and with analytic interpretations. Agreement is good for most objects. Those that fragment to many large objects should be treated by the decomposition of the radiation signal into its contributions from different fragments.

Earlier notes^{1,2,3} derived a model for the hydrodynamics, ablation, and radiation of meteor impacts at the level needed to infer meteor parameters from observations and extended it to objects that fragment during entry,⁴ using models⁵ based on related cometary studies.^{6,7} This note completes the comparison of the resulting filter model⁸ to European and Prairie Network (EN and PN) data and models of meteor impact. In cases of mutual applicability, U.S. and European models give broadly consistent results. The quantitative analysis of the EN and PN data is best discussed in conjunction with the Russian program of its analysis, because the Russian program has bypassed the large reported photometrically based masses to derive more plausible estimates of sizes, masses, and radiation efficiencies, which are the primary quantities of concern here.

This note completes the discussion of the PN and EN data begun earlier, uses the data to produce filter predictions, and compares it with observations and the predictions of the Russian analytic effort. The overall agreement is useful in that the Russian efforts have employed more complex models that use observational data directly, while the filter model is at a level of simplification much better suited to data inversion.

The discussion uses criteria defined by the PN, EN, and Russian efforts to identify likely breakup candidates, which reduces the observations to 6 large PN and 2 large EN objects, for which comparisons are carried out in detail at the level of both analytic filter models and detailed numerical calculations. The initial comparison showed that four objects correlated very well with the observations and mass inferences. Three of the remaining objects came into agreement through detailed numerical calculations of their entry conditions. The remaining discrepancy is the Benesov bolide, for which the filter mass agrees with the light curve to within about a factor of two, but for which the full explanation of the observations must take into account the distinct fragments from four separate fragmentations. The total light curve could be synthesized by the superposition of depositions at successively lower altitudes. Overall, the European and Prairie Network observations provide a useful data base of large objects for a successful test of the filter model and comparison of it with other numerical analyses.

European and Prairie Network (EN and PN) film- and video-based entry observation network has been in operation for a number of decades. It is the successor of visual observation programs of the previous century.⁹ Its advantage is its ability to triangulate positions and trajectories of objects and use established photometric correlations to estimate sizes; its limitations are its restricted geographic coverage, time resolution, and calibration. The networks have observed hundreds of objects, most much smaller than a meter.

The observations of greatest interest here are those in Table I, which show the impacts of meteoroids larger than 1 m.¹⁰ There are a total of 14 objects, ranging from the 10 m daylight Earth-grazing object of 10 August 1972 to the 1 m object of 14 August 1963. The interval spanned is from 1959 to 1994, about 35 years, so the average impact rate is about 0.4/yr. For the 10 m daylight Earth-grazing object of 10 August 1972, the row entries are its approximate 10 m diameter, -19 magnitude, 1,000 ton initial photometric mass, maximum brightness altitude $h_M = 58$ km, beginning luminous altitude $h_B = 76$ km, ending luminous altitude $h_E = 102$ km, angle of incidence $\cos\theta \approx 0$, initial velocity $v_\infty = 15$ km/s, and ending luminous velocity $v_E = 14.2$ km/s. The elements of orbit are of less concern. A useful by product of the PN and EN observations is the table below, which is inferred largely from observations of smaller objects¹¹

Table II. Survey of large meteoroid populations (source: Ceplecha Table I)

<u>type</u>	<u>assumed composition</u>	<u>density</u>	<u>ablation</u>	<u>strength</u> ¹²
I	stony	3.7g/cc	.017 s2/km2	1000 bar
II	carbonaceous	2	.041	100
IIIA	cometary	.75	.1	10
IIIB	soft cometary	.27	.21	1 ?

The type I, II, and IIIA objects correspond to the conventional stony, carbonaceous, and cometary material, e.g., the 10 m daylight Earth-grazing object of 10 August 1972 is identified as a type II carbonaceous object. At 15 km/s, at 58 km it should produce a pressure of about 1 bar. That should not fragment a large carbonaceous object, although it may have, in that its ending luminous altitude was higher than its beginning luminous altitude.

The type IIIB objects are of very low density, easily ablated, and generally fragment at very high altitudes. A significant number of them have been seen in the PN and EN observations. More than a third of the large objects in Table I are of type IIIB. The fractions of IIIA and I objects fall from about 35 and 15% at 0.1 m to 15 and 10% at 1 m and 5 and 1% at 10 m, which means stony and cometary objects are a minority at large sizes. Carbonaceous II objects are 30-45%, and IIIB increases from 20 to 60%. Thus, on the basis of this data, most objects larger than 1 m are expected to be stony or cometary.

When the objects from Table I are displayed according to their observed altitude of maximum brightness and inferred strength, they fall into three groups: stony Pribram by itself; the carbonaceous PN40503 through the Earth-grazing object; and the soft cometary Wurzberg through PN40401. Ideally, they should fall along a straight line; in practice they exhibit order of magnitude scatter.¹³ Pribram is far to the right and above the line, which indicates either an order of magnitude less strength than inferred or two orders of magnitude less penetration of density. While PN39470, PN39434, Freising, and Otterskir are close to the line, PN40503 and Beneslov are well below it, indicating greater strength; and the Grand Prairie and Earth-grazing events are well above it, indicating less. In the cometary objects, PN40401 is the furthest from the curve, indicating less penetration ability than expected.

Russian analysis of PN and EN data. Russian scientists have been engaged in the interpretation of meteor impacts for much of this century. In the process they developed a number of theoretical models to predict the radiation efficiency of impacting objects. Noting that the radiation magnitudes for the large objects in Table I were much smaller than the Russian models would produce for objects of the sizes cited, they examined the possibility that the objects were actually much smaller and radiated more efficiently. From a list of about 70 large PN and EN objects, which they examined in some detail, they produced the list of 19 large, well diagnosed impacts in Table III, from which they were able to infer masses.¹⁴

For example, object PN38737 was assigned a mass of 140 kg on the basis of photometrics and traditional meteor radiation efficiencies. On the basis of theoretical radiation efficiencies, the Russian effort led by Academician Nemtchinov was able to argue that its mass was on the order of 17-29 kg. This factor of two uncertainty depends on whether a heat of vaporization of 1-10 MJ/kg is used; the data do not unambiguously differentiate between them. These values were confirmed by the estimates of Kulakov (Mk) and Wetherill and ReVelle (MdR). The value due to Ceplecha (Mdc) is a confirmation of the PN photometric estimates. There is reasonable accord on the magnitude of the masses, although there are still factor of two uncertainties due to interpretation and uncertainties in physical parameters such as heat of vaporization and material strength. The maximum pressures show considerable scatter around the ideal values assigned to the various classes in Table I, indicating that there is considerable variation within each class.

An important subset of Table I is the objects with Ceplecha grading MF ("multiple fragments") and/or "Our (Nemtchinov) grading Y" (Yes, fragmentation). The other observations have been shown by Nemtchinov to be well represented by a non-fragmentation ablation model of the type used in deriving the filter model.¹⁵ The fragmenting objects can be used to test the breakup model. Table IV provides a more recent tabulation of observations of fragmenting

objects, together with an indication of the uncertainties in the theoretical reduction of the observations, which are factor of two overall.¹⁶

Table VI provides the measured velocity and height of maximum radiation for the large objects, along with their photometric mass (M_c) and radiation efficiency and theoretical mass (M). and radiation efficiency. Table VI provides additional information on radiated energy. It also shows that the theoretical masses are typically an order of magnitude smaller than photometric masses and that their radiation efficiencies are correspondingly an order of magnitude larger.

Table VII collects the data on the six large PN objects, which are indicated as fragmenting in Table III, plus two of the largest EN objects from Table I. It gives the PN or EN designation, name, Cepolecha type categorization, initial velocity, radiation efficiency f , peak power, assumed density, altitude of maximum radiation, filter diameter, filter mass, Russian inferred mass, kinetic energy (based on inferred mass), duration of light pulse, (cosine of) angle of incidence with respect to the radiant, observed strength, and the approximate strength used in filter calculations.

Figure 1 shows the inferred radiation efficiency as a function of inferred object mass. For objects larger than about 100 kg, the radiation efficiency increases roughly in proportion to the mass. For smaller masses it is roughly constant at about 1%. Overall, the scaling is approximately $f \sim 0.01$ for $M < 100$ kg and $\sim M/10000$ for larger M . Figure 2 shows the radiation efficiency as a function of inferred energy, which shows a break at about 100 GJ. For smaller energies $f \sim 1\%$; for larger energies $f \sim E/10000$.

Filter analysis. The PN and EN observations give both velocity and peak power. Thus, it is possible to substitute the filter expression for the velocity into that for the power and solve the filter equations directly for the approximate object diameter¹⁷

$$D_a \approx (5P_{\max} q^{4/3} / f b^{2/3} \rho_a V_o^3 V_o^3)^{1/2}. \quad (1)$$

The resulting object approximate mass, $M_a \approx \rho_a D_a^3 / 2$, is given in Table VII along with the mass M_i inferred by the Russian analyses in Tables IV-VI. Those masses are also shown graphically in Fig. 3, in which the diagonal line would represent complete correlation between the analyses, i.e., $M_a = M_i$, and the distance of the pairwise points from the diagonal represents the extent of their decorrelation. Four points lie close to the line: PN 30496A, 40590, and 40503 and EN 41274 (Sumava). They represent a range in mass from about 40 to 4,000 kg, two orders of magnitude spanning the most frequent fragmenting impactors. However, the model underestimates the masses of PN 39434, PN 40141A, PN 39470, and EN 70591 (Benesov); it is instructive to examine why that is so as well.

Figure 4 shows the experimental light curves for four of these objects. Panels c and b represent bolides 39406A and PN 40503, whose light curves show long exponential growth

interrupted by the faster growth expected after fragmentation. For each, the intensity increases by an order of magnitude or more during this final spike, as predicted by models of the rapid increase in the radiating area of multi-fragment debris clouds. These two bolides exhibit essentially classical fragmentation. Not unexpectedly, they lie very close to the correlated diagonal in Fig. 2.

PN 39406A. Figure 5 shows the power versus altitude (P vs z) from a detailed calculation of the entry of object PN 39406A using the PN measured velocity and Russian inferred mass, with which the filter agrees, performed with the numerical code developed in the derivation of the filter model.¹⁸ It shows that for the observed strength (ram pressure at peak altitude) of 25 bars, the object fragments at about 33.4 km and decelerates at about 32.5 km, which bracket the measured 33 km of peak radiation. The width of the peak is only one km. Its magnitude is about 1 GW/sr, which agrees with that of Fig. 4c. Figure 6 shows the power versus time from the detailed calculation, which indicates that the radiation pulse is about 0.06 s in duration, in good agreement with the 0.07 s estimated by the filter in Table VII.

PN 40503. Figure 7 shows P vs z for PN 40503, which also correlates closely with the filter. It is a reasonably large and fast object, which for a nominal strength of 100 bar fragments at about 26 km and decelerates sharply at 25 km, in accordance with observations of its deep penetration and with the assumptions of the fragmentation portion of the filter model. The peak radiation is about 5 GW/sr in agreement with the observations. However, Fig. 4b shows two peaks in its radiation, which indicates the production of two or more large, distinct fragments. Apparently, one fragments was slightly stronger, so that it penetrated about a km deeper. This level of detail in individual fragmentations is interesting, but it cannot be predicted ab initio on the basis of current data. However, the agreement on aggregate observables is again very close.

PN 40151A. Figure 4a for bolide PN 40151A shows quite different behavior. Its growth is exponential throughout. There are a number of small peaks, but no large single peak. It does not appear to fragment; thus, it is not appropriate to use the fragmentation filter for it. It is not clear why this object was identified in Table III as possibly fragmenting by the Russian and PN analyses. Not surprisingly, the point for this object lies well off the diagonal, as the absence of a strong radiation peak causes Eq. (1) to assign it a small approximate diameter and mass.

Figure 8 shows P vs z from a detailed calculation of PN 40151A using the filter and inferred masses of 1.6 and 40 kg. The radiation efficiency used for the former is the 1% from Fig. 1. The filter mass fragments at about 36 km and decelerates at 35 km. The inferred mass decelerates more gently at about 34 km. The altitude difference between these two peaks would not be observable with the sensors used. The principal difference is that the inferred mass produces a peak radiation of 0.03 GW/sr, while the filter mass produces a maximum of about 0.003 GW/sr, which is much closer to the ~ 0.002 GW/sr shown in Fig. 4a. Thus, it would appear

that the filter gives a better match to the main radiation observable than does the inferred mass. Unfortunately, the Russian reports do not provide enough information for an evaluation of the reasons for the difference.

PN 39470. Figure 4d for bolide PN 39470 also shows a smooth shape with no sharp peak in radiation, which indicates that it does not fragment. Thus, the fragmentation filter is not strictly appropriate. Moreover, Tables III-VI show that Russian estimates of its mass have varied from 190 to 1,740 kg over the last two years, with the current range being 700-1250 kg, so it is not clear that the discrepancy shown is a deficiency of the fragmentation model.

Figure 9 shows that the inferred parameters produce a radiation pulse extending over about 1 km with a peak of about 3 GW/sr, which is about a factor of three larger than the peak in Figure 4d. The filter curve shows the prediction for a 500 kg object of strength 75 bar, which fragments at about 31 km, decelerates at 30.5 km and radiates a peak of about 1 GW/sr, which is much closer to the observations. The numerical calculation's pulse length of ~ 0.05 s is also in reasonable agreement with the filter's 0.08 s.

Thus, a mass of 500 kg appears to be in better agreement with the data. However, both of the curves in Fig. 9 radiate their energy in a km or less, whereas the curve in Fig. 4d appears to spread it over about 5 km. That indicates that the smooth curve may conceal considerable fragmentation at higher altitudes, although it is not possible to determine that from the light curve of Figure 4d, which is heavily smoothed.

PN 39434. Figure 10 shows the light curve, radius, velocity, and mass history for PN 39434, nominally a $M_i = 500$ kg object for which the filter gives $M_a \approx 70$ kg. The light curve shows several small peaks, but the final one is only a 50% increase. The radius also increases about 50% at 33-27 km where the velocity falls sharply, but the mass continues to fall smoothly, which indicates that there is no sharp fragmentation. It appears that pieces instead sluff off continually, which is consistent with the small oscillations seen in the intensity throughout. Tables III-VI show that Russian estimates of the mass of PN 39434 have varied from 160 to 820 kg over the last two years, with the most recent range being 300-700 kg; thus, it is not clear how much of the discrepancy shown is due to the fragmentation model.

Figure 11 shows the result of a detailed calculation of PN 39434 for the inferred and filter masses. The two curves peak within about a km of each other in altitude and the observed value. The inferred mass has a width on the order of a few kilometers; the filter mass has a width on the order of one kilometer. The curves have similar rise and fall times, but the inferred mass produces a much higher peak radiation and a 2-3-fold longer pulse, so its radiated energy is an order of magnitude greater than that from the filter mass. The ~ 0.06 GW/sr peak from the filter mass is close to the observed 0.04 GW/sr. The inferred curve gives a value about $0.3/0.04 \sim 7.5$ -fold too high. Thus, the filter mass again gives a better approximation to the observed values.

PN 40509. Figure 12 shows the intensity, velocity, radius and pressure from PN 40509, the Lost City bolide. While the pressure increases, the radius shows little increase, and the velocity decreases smoothly, so fragmentation is unclear from these plots. One sensors saw a peak radiation of ~ 8 GW/sr at about 28 km; the other about 2 GW/sr at 32 km. There are small peaks in the intensity, but no indication of complete breakup. The inferred mass is about 100 kg; the filter mass is about 137 kg, which represents adequate correlation with each other and with the meteorites collected at the fall.

Figure 13 shows P vs z from a detailed calculation of PN 40509. The peak is at roughly the right altitude, but the magnitude is about 0.1 GW/sr, which is about a factor $0.1/0.007 \sim 14.3$ larger than the 0.007 GW/sr from Fig. 12. It would be necessary to reduce the mass an order of magnitude to reach that level. Thus, it would appear that the radiation efficiency of this object is reduced as well.

A second discrepancy is that Fig. 12a shows significant radiation all the way from 50 down to ~ 30 km, while the numerical prediction has a sharp onset at 33-35 km when the object breaks. This implies that the object fragments often and continuously all the way down, which would produce the repeated flashes seen at high altitudes. That phenomena is not incorporated in the approximate filter calculations. Overall, PN 40509 is an example of an object for which the inferred, filter, and calculated parameters show good agreement with each other but have significant quantitative and qualitative disagreements with the data.

EN 70591. Figure 4 shows the magnitude, velocity, radius, and mass of EN 70591, the Benesov bolide, which is the largest penetrating EN object for which enough information is available for a detailed assessment. The magnitude shows exponential growth to about 35 km, a peak, a decrease, a rise to a second peak at about 24 km, and then a sharp decrease. The radiometric radius inferred from these magnitudes also shows sharp increases at 35 and 24 km. The mass and velocity decrease smoothly throughout. The inferred total mass is about 2,500 kg; the filter mass for the lower object is about 170 kg.

Figure 15 is from a detailed calculation of the second and lower fragmentation of EN 70591. The top curve for the inferred mass is about 8 GW/sr, which is about a factor of 6.7 larger than the observed value of 1.2 GW/sr. The lower curve for the filter mass peaks at about 4.5 GW/sr, which is a factor of two below it. The correct value for the lower fragment would appear to lie somewhere between the two and somewhat closer to the latter.

Benesov is actually somewhat more complicated than these curves would indicate. Figure 16 shows the shower of breakup fragments deduced by the Russian investigators from the EN 70591 record. It shows a total of eight large fragments that are produced in four major fragmentations at 38, 34, 32, and 24 km. While the fragments at 24 km tend to remain together,

those at higher altitudes have quite different trajectories, so detailed analyses would have to be made to determine the total light output.

It appears that the curve for a 170 kg fragment like the lower curve in Fig. could be replicated and translated to other altitudes to approximate the overall light output. That process is complex for Benesov, but can be executed for some other examples, as discussed below.

EN 41274. Figure 17 shows P vs t from EN 41274 Sumava, a very large and bright type IIIB object that produced its light at about 62 km. It is encouraging that the filter model formulated for an calibrated on penetrating, fragmenting objects should reproduce the inferred value of its mass this closely, given the apparent number of large IIIB objects. The light curve shows significant power and structure from about 1 to 2.5 s.

The curves overlaid on P vs t are essentially the component curves of Fig. 15, translated into the time domain. It is clear that roughly three such curves could match the peaks in the curve at 1.5, 2.1, and 2.5 s. Because each curve contributes primarily at its peak, the contributions from curves for other peaks are small, so the decomposition essentially amounts to subtraction. For other objects with distinct peaks, decomposition could be performed similarly. The filter equations are accurate enough to do that subtraction. Because they explicitly contain the dependence of power on mass per object, it should be possible to determine the mass in each peak as well.

Summary and conclusions. The PN and EN data provide a useful basis for testing the filter model and for comparing it to other models for inferring the masses of its observations. To do so, this note completes the discussion of the PN and EN data, extracts auxiliary quantities such as parametric radiation efficiency, uses the data to produce filter predictions, and compares those predictions with the data and with those of the Russian analytic effort. The overall agreement is generally quite good. That is useful in that the Russian efforts have employed more complex models that use observational data directly to achieve agreement, while the filter model is at a level of simplification much better suited to data inversion.

The discussion uses criteria defined by the PN, EN, and Russian efforts to identify likely breakup candidates, which reduces the 60 candidates down to about 6 large PN and 2 large EN objects, for which comparisons are carried out in some detail—both at the level of analytic filter models and detailed numerical calculations.

The initial comparison showed four objects that correlated very well with the observations and the Russian mass inferences. Each of them represented a fairly convincing fragmentation and rapid deceleration following the theoretical models. Each of the four objects that disagreed did so for a different reason. The smallest mass was marginal for fragmentation, but when a detailed calculation of its radiation was performed, it appeared that the filter mass gave a much closer approximation to the observed light curve than the inferred mass. The data

do not support a fuller resolution of this issue. The two ~ 100 kg objects also recalculated to values much closer to the filter values.

The remaining discrepancy is the Benesov bolide, for which the inferred total mass is about 2,500 kg, and the filter mass for the lower object is about 170 kg. The filter mass gives a power about half that observed, which is much closer than that from the inferred mass. But the full explanation of the observations must take into account the numerous distinct fragments from the four separate fragmentations observed, which produced a total of about 8 large objects. If each had 12% of the total inferred mass, or ~ 300 kg, the total light curve could be synthesized by the superposition of depositions at successively lower altitudes. That is difficult to perform with Benesov, but is apparently possible with Sumava, where there are only three fragments and they are well separated in time.

Overall, the filter produces results that are broadly consistent with the data and with Russian inferences from it. A by product of those analyses is a test of the classifications EN and PN use for stony, carbonaceous, and cometary materials. EN and PN observations indicate that most objects larger than 1 m are expected to be stony or cometary, which is consistent with the values inferred from accurate reconstructions of trajectories. Trends in magnitude correlate reasonably well with measured velocities, altitudes, and trajectories and inferred size and strength parameters; however, parameters are subject to uncertainties of factors of two; masses to an order of magnitude, and the strengths to a like amount. Thus, while the European and Prairie Network observations provide a useful data base for large objects, these uncertainties directly effect the sensitivity of predictions of object parameters. That said, they provide a good test of the filter model and a useful basis for the comparison of it with other numerical analyses in which the overall agreement is more than adequate.

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Table I. Bodies with size over 1 m with data derived from photographic observations of their fireballs. (Data on the "Daylight Earth-Grazing" fireball were derived from infrared tracking). (Source: Ceplecha)

number	Daylight	EN041274	PN40503	EN170171	PN39470	EN070591	PN39121
name	Earth-Grazing	Šumava		Würzburg		Benešov	
year date	1972 Aug 10	74 Dec 4	69 Oct 9	71 Jan 17	66 Dec 11	91 May 7	65 Dec 27
time UT	20 ^h 29 ^m	17 ^h 56.6 ^m	7 ^h 16 ^m 39 ^s	18 ^h 20 ^m	1 ^h 12 ^m 00 ^s	23 ^h 03 ^m 58 ^s	8 ^h 21 ^m 05 ^s
size [m]	(10)	7.1	2.6	2.2	2.0	1.9	1.9
M_{max}	(-19)	-21	-20	-17	-18	-18.5	-12.1
m_{∞} [kg]	10 ⁶	50000	17000	1600	8500	7500	1000
$h_{M_{max}}$ [km]	58 *	73	23	60	33	26	72
h_B [km]	76	99	93	75	79	98	96
h_E [km]	102	55	21	45	22	16	61
$\cos z_R$	$\approx 0.$	0.460	0.619	0.248	0.559	0.986	0.857
v_{∞} [km/s]	15.08	27.0	21.0	15.7	23.6	21.086	23.8
v_E [km]	14.21	26.	11.	11.	9.3	2.	13.6
a [AU]	1.661	1.472	1.98	2.02	2.35	2.11	2.428
e	0.390	0.363	0.76	0.64	0.62	0.71	0.619
q [AU]	1.0127	0.9369	0.471	0.722	0.901	0.613	0.9246
Q [AU]	2.31	2.006	3.5	3.3	3.8	3.7	3.93
ω [deg]	355.6	315.76	282.0	73	321.0	265.1	218.65
Ω [deg]	317.956	317.949	251.78	16	116.75	259	46.314
i [deg]	15.22	6.93	2.3	12.6	2.71	0.8	23.70
type	(II)	IIIB	II	IIIB	II	II	IIIB
note	infrared tracking	4 GS	28-5 Å/mm		2 GS		
						67-22 Å/mm	
number	EN070459	EN 010677	EN100469	PN39434	MORP 925	PN40401	EN140863
name	Přibram	Freising	Otterskir.		G. Prairie		
year date	59 Apr 7	77 June 1	69 Apr 10	66 Nov 5	84 Feb 23	69 June 29	63 Aug 14
time UT	19 ^h 30 ^m 21 ^s	21 ^h 46 ^m	21 ^h 44.5 ^m	10 ^h 41 ^m 11 ^s	2 ^h 16 ^m	9 ^h 25 ^m 13 ^s	21 ^h 48 ^m 34 ^s
size [m]	1.8	1.4	1.3	1.3	1.2	1.1	1.0
M_{max}	-19.2	-17	-15.4	-14.2	-14.9	-14.0	-15
m_{∞} [kg]	11000	2600	2500	2100	2000 **)	200	140
$h_{M_{max}}$ [km]	46	41	45	32	48	92	82
h_B [km]	98	78	84	77	91	104	103
h_E [km]	13	27	24	27	(30)	72	69
$\cos z_R$	0.678	0.328	0.569	0.512	≈ 0.1	0.500	0.948
v_{∞} [km/s]	20.886	27.0	16.1	14.6	26.5	19.2	24.6
v_E [km]	(3)	5.2	≈ 3	≈ 7	(4)	17.5	≈ 24
a [AU]	2.401	1.8	2.32	0.71	1.93	3.80	3.01
e	0.671	0.75	0.60	0.43	0.73	0.76	0.67
q [AU]	0.7894	0.455	0.934	0.405	0.515	0.907	1.006
Q [AU]	4.01	3.2	3.7	1.02	3.35	6.7	5.0
ω [deg]	241.75	286	35.1	196.7	97.6	221.3	190.31
Ω [deg]	17.110	71.01	200.561	42	153.18	97	141.192
i [deg]	10.48	1.5	6.77	3.4	8.4	13.1	35.1
type	I	II	II	II	II	IIIB	IIIB
note	meteorites recovered						PS

*) at perigee

**) photometric mass from $\int I dt = 7.07 \times 10^6$ given by Halliday (1985)

size initial size before entering the atmosphere

 M_{max} maximum absolute (100 km distance) magnitude m_{∞} initial mass transformed to the same corrected scale as used in papers of Ceplecha (1988, 1992) $h_{M_{max}}$ height at the maximum brightness h_B, h_E height at the beginning and at the end of the luminous trajectory, respectively $\cos z_R$ cosine of the zenith distance of the radiant v_{∞} initial velocity before entering the atmosphere v_E velocity at the end of the luminous trajectory $a, e, q, Q, \omega, \Omega, i$ orbital elements (1950.0)

note GS... grating spectra available PS... prism spectrum available

Table 1.1.

Table III. PN mass estimates (Source: Nemtchinov, 30 Nov 95)

Estimates of bolide's mass (PN is a number in catalogue (McCrosky et.al., 1978, 1979), M_{ph} is a photometric mass, M and M_N are is present work mass estimate based on "old" and "new" data, classification in terms of fragmentation and type of meteoroid (Cepilecha (1995)), maximum loading pressure, estimates of dynamical mass according Kulakov and Stulov (1992) (M_k), Cepilecha (1995) (M_{dc}), Wetherill and ReVelle (1981) (M_{dR}).

PN	M_{ph} kg	$Q = 10^6 \text{ J/kg}$		$Q = 10^7 \text{ J/kg}$		Cepilecha grading	Our grading	Maximum pressure M_{dyn}/cm^2	M_{dc} kg	M_{dR} kg
		M_k kg	M kg	M_N kg	M kg	M_N kg				
38737	140	12-17	17	-	29	-	-	U	17	-
38768	160	8-12	16	-	27	-	-	N	24	-
39113A	34	8-10	6	6	10	9	NF, II	U	24	98
39138B	155	3	2.6	2.7	3	3.2	NF, II	N	44	150
39406A	260	7.2-7.1	19	13	33	21	MF, II	— Y	23	92
39434	2120	34	160	200	350	283	NF-MF, I	— U	18	3650
39470	8500	650	187	-	271	-	-	Y	123	-
39499	30	4-7	21	23	32	32	-	U	4	-
39512	40	25	4	-	7	-	-	U	44	-
39681	405	26	32	-	67	-	-	N	18	-
39921C	55	3.7	10	-	15	-	-	U	25	-
39935	550	7-11	4	4.4	7	7	NF-MF, I	— U	44	28
40151A	170	2-15	28	28	39	35	MF, I	— Y	24	42
40161	39	11-12	9	5.1	16	9.5	NF-MF, II	N	13	320
40405	35	3.5	12	13	21	20	1F, II	U	10	83
40503	17500	76-151	115	125	162	185	NF, II	— Y	95	2400
40590	245	32-52	40	42	56	46	2F, I	— Y	29	205
40617	39	5-8	14	14.2	22	20	-	U	12	-
41275	155	44	15	-	20	-	-	Y	29	-

Table IV. Recent PN masses (Source: Nemtchinov, 17 Apr 77)

Table 3.1.

Estimates of bolide's mass (PN is a number in catalogue (McCrosky et. al., 1978, 1979)), M_{ph} is a photometric mass, classification in terms of fragmentation and type of meteoroid (Ceplecha et al., 1996), maximum loading pressure, estimates of dynamical mass according Ceplecha (1995) (M_{dc}), our mass estimate M obtained in the framework of AP model and S method and in assumption of all bolides to be H-chondrites. Two values of energy conversion were used (380J/0-mag and 840J/0-mag).

PN	M_{ph} kg	Ceplecha grading	Our grading	Coincidence between the light curve analysis and trajectory analysis	Maximum pressure M_{dyn}/cm^2	M_{dc} kg	M kg
38737	140	-	U		17	-	24-50
38768	160	-	N		24	-	24-52
39080A	16.5	NF, I	N	+	22	2.9	1-3
39113A	34	NF, II	U	-	24	78	7-14
*39138B	155	NF, II	U	-	44	150	6-10
39240	30	NF, I	U	-	35	16	5-11
39404	19.5	1F, I	Y	+	9	2.2	6-13
39406A	260	MF, II	Y	+	23	73	32-66
39425	23.5	NF-MF, II	N	+	5	21.5	3-10
39434	2120	NF-MF, I	Y	+	18	2904	300-720
39450	8	1F, I	U	-	23	4.8	2-4
39470	8500	-	Y		123	-	700-1250
39499	30	-	Y		4	-	13-29
39512	40	-	U		44	-	8-17
39681	405	-	N		18	-	108-215
39794B	5.5	NF, II	N	+	17	23.1	1-3
39921C	55	-	U		25	-	11-24
39935	550	NF-MF, I	U		44	22.3	5-10
39910	9.5	NF-MF, I	U		20	2.2	1.5-3.2
39911	24	NF, I	N	+	60	47.8	4-8
40151A	170	MF, I	Y	+	24	33.4	29-63
40161	39	NF-MF, II	N	+	13	254.7	6-14
40405	35	1F, II	Y	+	10	66	11-24
40503	17500	NF, II	Y	-	95	1910	400-750
40590	245	2F, I	Y	+	29	163	52-150
40617	39	-	U		12	-	12-25
41275	155	-	Y		29	-	15-32

Ceplecha Grading: according to the dynamical trajectory analysis (Ceplecha, 1995).

NF - non fragmented;
MF - multi fragmented;

1F - 1 stage of fragmentation;

I - type I, $\rho = 3.7 \text{ g/cm}^3$;

II - type II, $\rho = 2.0 \text{ g/cm}^3$;

Our grading:

Y - yes, fragmented; U - unidentified; N - non fragmented.

Table V. PN velocity, efficiency, and height
(Source: Nemtchinov, 1 Mar 96)

Estimates of bolide mass (M -present work, M_c - Cepplecha et al., 1996), integral luminous efficiencies in panchromatic bandpass assuming 840J/O-mag (τ - present work, τ_c - Cepplecha et al., 1996), height of maximum intensity h_{max} and bolide entry velocity V .

Table 7.2

PN	type	V, km/s	M_c , kg	τ_c , %	M, kg	τ , %	h_{max} km
39080A	I	32.53	2.9	5.26	2.8	5.98	56.7
39113A	II	15.127	77.98	0.20	14.0	1.16	33.7
39240	I	17.25	15.89	1.13	11.4	1.65	29.3
30404	I	15.44	2.21	5.05	12.8	0.92	46.5
* 39406A	II	17.23	73.11	1.64	66.0	1.94	32.5
39425	II	19.73	21.48	0.81	10.0	0.72	54.5
* 39434	I	14.31	2904.02	0.28	820.0	0.95	32.3
39450	I	24.51	4.78	1.19	4.0	1.50	39.7
39794B	II	21.83	23.07	0.18	3.0	1.38	38.7
39910	I	21.95	2.23	3.48	3.2	2.36	36.5
39911	I	30.57	47.75	0.48	8.4	2.63	38.7
39935	I	17.75	22.28	1.36	9.8	1.76	36.3
* 40151A	I	13.45	33.42	1.38	63.0	0.76	31.8
40161	II	16.87	254.68	0.10	13.5	2.12	50.0
40405	II	14.7	65.92	0.32	24.0	1.03	42.6
* 40503	II	20.86	1909.85	2.31	939.0	5.10	23.4
* 40590	I	14.15	162.93	0.85	150.0	0.93	31.7

Table 7.3

PN	type	V, km/s	M_c , kg	τ_c , %	M, kg	τ , %	h_{max} km
38737	II	17.1	-	-	50	1.94	39.9
38768		17.6	-	-	52	2.42	53.6
! 39138B		30.7	-	-	17	2.27	34.7
39470		23.6	-	-	1740	3.80	33.3
! 39499		12.4	-	-	29	0.38	48.3
39512		20.1	-	-	17	1.84	35.8
39681		20.8	-	-	215	1.61	40.2
39921C		14.5	-	-	24	0.94	31.9
! 40617		13.2	-	-	25	0.61	35.5
41275		13.1	-	-	32	0.67	31.0

Table VI. PN radiated energy (Source: Nemtchinov, 30 Nov 95)

Table 1.2

Some parameters of bolide's under consideration.

PN is a number in catalogue (McCrosky et.al., 1978, 1979), M_{ph} is a photometric mass, V_0 is entry velocity, M is present work mass estimate ($Q = 1 \text{ MJ/kg}$), E_r is emitted energy, τ_1 and $\tau_1(M_{ph})$ are the integral luminous efficiencies, obtained based on our mass estimates and using photometric mass.

PN	V_0 km/s	M_{ph} kg	M kg	E_r MJ	$\tau_1(M_{ph})$ %	τ_1 %
38737 *	16.9	140.0	17	13.8	0.068	0.56
38768 *	17.6	160.0	16	19.4	0.078	0.80
39113A	14.9	34.0	6	1.8	0.048	0.26
39138B	30.7	55.0	3	17.0	0.066	1.40
39406A	17.1	260.0	15	18.3	0.048	0.82
39434	14.5	2120.0	200	80.0	0.036	0.37
39470 *	23.6	8500.0	187	1822.7	0.078	3.53
39499	12.4	30.0	24	0.8	0.034	0.04
39512 *	20.1	41.0	4	6.0	0.074	0.80
39681 *	20.8	405.0	29	71.0	0.082	1.18
39921C *	14.5	55.0	10	2.3	0.040	0.23
39935	17.8	55.0	4	4.7	0.054	0.73
40151A	13.4	170.0	28	4.1	0.028	0.16
40161	17.0	39.0	6	3.8	0.068	0.45
40405	14.8	35.0	12	2.5	0.066	0.20
40503	20.6	17500.0	114	1032.9	0.028	4.15
40590	14.2	245.0	40	4.3	0.018	0.11
40617	13.2	39.0	14	0.2	0.006	0.02
41275 *	13.1	55.0	15	1.8	0.038	0.15

* Bolides, for which meteorite falls were proposed, are marked by stars.

Table 1.3.

PN	$8.32 \cdot 10^8$	$5.25 \cdot 10^9$	$8.4 \cdot 10^9$	M_{ph}
39113A	5.8	17	25	38
39138B	2.7	7.8	11.8	55
39434	201	540	757	3200
40590	42	120	170	260

PN DATA & ANAL

Table VII. Parameters for fragmenting PN and EN objects.																
Designation	Name	Cepl	V m/s	f	P GW/sr	rha	Zm	ct	D	Mfilter	Minf	EGJ	t(s)	cosx	S obs	Sa
PN39406A			17,100	0.02	0.1	2,000	33		0.35	44.401	45	6.58	0.07		26.22	25
PN39434		II	14,300	0.01	0.04	2,000	32		0.41	69.436	500	51.1	0.1	0.6	20.26	10
PN39470		II	23,600	0.035	1	2,000	33		0.52	142.3	1,000	278	0.08	0.6	49.94	20
PN40151A			13,400	0.008	0.002	2,000	33		0.12	1.6061	40	3.59	0.03		16.1	10
PN40503		II	20,600	0.05	5	2,000	24		0.78	476.46	650	138	0.06	0.6	137.6	100
PN40590	Lost City		14,200	0.009	0.06	2,000	32		0.52	136.8	100	10.1	0.12		20.86	20
EN70591	Benesov	II	21000	0.03	1.1943	2,000	27		0.55	168.31	2500	551	0.05	1	93.18	50
EN41274	Sumava	IIIB	27000	0.2	7.5357	2,000	62		1.94	7330.6	4000	1458	4.08	0.5	1.038	1

Fig. 1. Radiation efficiency vs inferred mass

$2 f v E i$

Fig. 2. f vs E

$E(\text{GJ})$

Fig. 3. M inferred vs M approx

Fig. 4. PN LIGHT CURVES

Fig. 7.1.

Light curves of some bright PN bolides (two biggest bolides are PN 40503 (b) and PN 39470 (d)) in dependence on height. The energy conversion factor of 840J in panchromatic bandpass was used.

Fig. 5. P vs z for PN 39406A

Fig. 6. P vs t for PN 39406A

Fig. 7. P vs z PN 40503

Fig. 8. P vs z for PN 40151A

Fig. 9. P vs z PN 39470

Fig. 10. bolide PN 39434

Fig. 7.6.

Observed intensity (a), and radiation radius (b), velocity (c) and mass (d) versus height obtained in the simulations for the bolide PN 39434 assuming it to be H-chondrite. Experimental data on the velocity is given by squares.

Fig. 11. P vs z PN 39434

Fig. 12. bolide PN 40590 (Lost-City)

Fig. 7.3.

Light curves corresponding to different recordings for bolide PN 40590 (Lost-City) in dependence on height (a) and time (b) are shown. The energy conversion factor of 840J to zero stellar magnitude in panchromatic bandpass was used. The radiative radii, pressure loading (d) and velocity dependencies (c) on height are given. Black squares correspond to the catalogue data (McCrosky et al., 1978).

Fig. 13 P vs z PN 40590 Lost City

PVZLC

Fig. 14 Benešov bolide

Light curve of Benešov bolide (a) and result of numerical simulations using model S - radiative radius (b), calculated velocity and the observed one (pointed curve) (c), mass estimate (d).

Fig. 15 P vs z EN 70591 Benesov

Fig. 16 Benešov fragments

Velocity curves of the fragments of Benešov bolide as determined from fitting and extrapolation from the gross-fragmentation model. The thick segments represent the intervals where the velocity was measured. Thin solid lines represent the extrapolation of fragment velocities and the dashed lines belong to hypothetical fragments not directly seen

(Source: Nemtchniov)

Fig.17 Sumava radiation

Radiation power of the Šumava bolide:

A solid curve is the results of observations, Dashed curves are the results of modeling with three separate fragments. Parameters of the fragments are given in Table 3.1.