Title:

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OBSERVATIONS OF METEOR IMPACT**

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COMPARISON WITH EUROPEAN OBSERVATIONS OF METEOR IMPACT

Gregory H. Canavan

A model for the inference of object size and speed from observations is used to discuss European observations of impact. It compares the observed and predicted breakup altitudes for the objects larger than one meter and observes useful correlations. Trends in magnitude correlate well with measured velocities, altitudes, and trajectories and inferred size and strength parameters, but each parameter is subject to dispute, which can only be addressed when the sensitivity of predictions to uncertainties in these parameters is assessed.

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. The full model is presented in "Fragmentation and Ablation During Entry,"⁴ which is reviewed briefly below. The previous note⁵ compared it to other U.S. models with different but related features and objectives. The most closely related model is that due to Hills and Goda,⁶ which solves the same equations numerically, uses a consistent treatment of fragmentation, and produces similar results for common parameters, although it does not treat radiation in detail and assumes constant heat transfer coefficients. A model due to Chyba, Thomas, and Zahnle⁷ differs primarily in its estimate of fragment spread velocities and variable heat transfer coefficients. Both of those models are primarily concerned with interpreting the large Tunguska impactor, so they simplify many features and concentrate on varying parameters such as heat of vaporization and material strength to try to match observed surface damage patterns. The previous note discussed models with zero-dimensional hydrodynamics, simplified radiation transport, constant heat transport, parametric fracture and spread, and limited recourse to the limited data on objects tens to thousands of meters across.

This note extends that discussion to European data and models of meteor impact. U.S. analyses have used simplified models to try to achieve agreement with the very limited data on large objects while the European efforts have used more complex models that use observational data more directly to achieve agreement for a larger body of data on smaller objects. While the former is at a level of simplification better suited to the model for data inversion needed for this effort, the latter represent a more thorough test of model sensitivities and uncertainties for objects in the size range of interest. Thus, it is also a useful test of the inversion model. In cases of mutual applicability, the U.S. and European models appear to give broadly consistent results.

This note puts the inversion model into a form appropriate for interpretation of the European and Prairie Network observations of 14 objects larger than 1 m in diameter. The EN and PN observations use largely consistent classifications of these objects into stony,

carbonaceous, and cometary materials and indicate that most objects larger than 1 m are expected to be stony or cometary. When these objects are displayed according to their observed altitude of maximum brightness, which is related to fragmentation altitude, and inferred strength in bars, they fall into three groups: one stony object, the carbonaceous objects, and the soft cometary objects. Ideally, they should fall along the theoretical line of pressure versus altitude; in practice they exhibit several order of magnitude scatter due to variations in material strength. Correcting pressure for entry velocity provides a more precise measure of deviations from theory. There is a strong correlation, but there is a great deal of spread within each group.

The quantitative analysis of the EN-PN data is better discussed in conjunction with the Russian analysis program, but some qualitative observations are useful. The change in magnitude of the 14 large objects with size and speed can be explained readily by the changes in their size, speed, trajectory, and type. Trends in magnitude correlate reasonably well with measured velocities, altitudes, and trajectories and inferred size and strength parameters. However, each parameter is subject to dispute. The sizes are uncertain to factors of two; the masses to about 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 can only be addressed when the sensitivity of predictions to uncertainties in these parameters is assessed.

Review of model for inversion of observations. Earlier notes developed a model for objects that ablate and fragment during entry.⁸ That model also provides a common framework for the discussion of European efforts. The inversion model is formed by complementing the equation for the conservation of momentum

$$M dV/dt = - C_p A V^2, \quad (1)$$

where M is the object mass, V is its instantaneous velocity, C is its drag coefficient, ρ is the local density, and A is the object area with an equation for the rate of change of mass due to ablation

$$Q dM/dt = - J_p A V^3, \quad (2)$$

where Q is the heat of vaporization and J is a heat transport coefficient, which is ≈ 0.1 at altitudes ≥ 30 km. For constant J , taking the ratio of Eqs. (1) to (2) and integrating produces

$$M = M_0 \exp[-K(1 - v^2)], \quad (3)$$

where M_0 and V_0 are the object's initial mass and velocity, $v = V/V_0$, and $K = J V_0^2 / 2 C Q$ is a parameter. The model is closed by assuming that fragmentation takes place when the ram pressure on the front of the object reaches its strength S , or

$$p \approx C_p V^2, \approx S, \quad (4)$$

After the object breaks up, its fragments are assumed to move apart at a transverse velocity of

$$V_t = k V \sqrt{(\rho/\rho_a D)}, \quad (5)$$

until they fall below the velocity of Eq. (4). Before fragmentation, the velocity can be approximated adequately by the form

$$V \approx V_0 e^{-\rho H / \beta \cos \theta}, \quad (6)$$

where $\beta = M/A \approx 0.7 \rho_a D$ is the areal density (ballistic coefficient) of an object of mass M , area A , diameter D , and density ρ_a and θ is the angle of incidence with respect to vertical. After fragmentation, V can be described by a function that is more complicated, but which remains analytically soluble, differentiable, and invertible. Once V and M are known as functions of altitude, it is possible to invert the solutions to infer the initial V_0 , D_0 , and angle of incidence from measured values of peak power, pulse duration, and altitude of maximum radiation.

Entry pressures. A useful by-product of this model is a prediction of breakup altitude as a function of object parameters. The pressure on the object's front surface is given by Eq. (4), where to adequate accuracy the velocity can be approximated by Eq. (6). Thus, the pressure is

$$p \approx C_p V_0^2 e^{-2\rho H / \beta \cos \theta}, \quad (7)$$

as shown in Fig. 1 as a function of altitude for vertical incidence at $V_0 = 20$ km/s for $D = 0.25$ to 4 m. The names are observed objects discussed in the next section. The pressures for all objects are within a factor of two above 20 km, where they scale as $p \approx C_p V_0^2 \sim \rho$. Because the pressure increases exponentially along with ρ , for large objects, the altitude of fragmentation is insensitive to the precise value of material strength, which is useful, as that parameter is poorly known. For larger objects, the peak pressure is larger at lower altitudes because they do not decelerate until $p \approx \beta/H \sim D$. Smaller objects decelerate and produce lower pressures.

At 20 km, the pressure reaches about 200 bars (atmospheres) for 1-4 m objects and 100 bars for a 0.25 m object. Pressure scales as V_0^2 , so at 10 km/s, the 4 m object would only reach 50 bars. In this approximation the angle of incidence enters only as $\beta \cos \theta \sim D \cos \theta$, so non-vertical incidence at $\cos \theta$ corresponds to vertical incidence of an object of diameter $D/\cos \theta$. At 25 km, 75 degree incidence ($\cos \theta = 0.25$) of a 1 m object would produce a pressure about $75/100 = 75\%$ that from vertical incidence. For reference, the nominal yield stresses for iron, stone, carbon, and comet materials are 1,000, 100, 10, and 1 bar.⁹ Thus, at 20 km/s, iron objects larger than 2m should reach the ground intact. Stone objects of meter sizes would fragment at about 25 km. Carbonaceous objects would fragment at about 40 km. IIIA comets would fragment at about 60 km, and IIIB comets might fragment at about 70 km, as shown in Fig. 1.

European and Prairie Network (EN and PN) impact observations. This film- and video-based observation network has been in operation for a number of decades; it is the successor of the visual observation programs of the previous century.¹⁰ Its advantage is its ability to triangulate positions and trajectories of objects and use established photometric correlations to estimate sizes; its limitation is its restricted geographic coverage. 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.¹¹ There

are a total of 14, 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 that the average impact rate is about 0.4/yr, although the rate is smaller for larger objects, as discussed further below.

For example, the 10 m daylight Earth-grazing object of 10 August 1972 row entries are its approximate 10 m diameter, -19 magnitude, 1,000 tonne initial 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, but a useful additional datum is the table inferred largely from observations of smaller objects¹²

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

<u>type</u>	<u>assumed composition</u>	<u>density</u>	<u>ablation</u>	<u>strength</u> ¹³
I	stony	3.7g/cc	.017 s ² /km ²	1000 bar
II	carbonaceous	2	.041	100
IIIA	cometary	.75	.1	10
IIIB	soft cometary	.27	.21	1 ?

This ablation parameter is related to the $K = JV_0^2/2CQ$ of Eq. (3) above. For $J \approx 2C$ and fixed V_0 , $K \sim 1/Q$, which for the $Q = 8, 5$, and 2.5 MJ/kg used in the earlier notes for stony, carbonaceous, and cometary objects, respectively, give K's in the ratio of 1, 2, and 4, in qualitative agreement with the progression seen in Table II for type I, II, and IIIA objects, respectively, although the numerical values are normalized differently. The category IIIB, i.e., very low density, easily ablated objects, were not treated in the inversion model. Note that Table I contains five IIIB objects, over 1/3rd of the total.

As an example, 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, which should not fragment a large carbonaceous object, although it may have in that its ending luminous altitude was higher than its beginning luminous altitude.

Another important datum, also inferred from observations of smaller objects, is Fig. 2, which gives the EN-PN estimates of the fraction of objects as a function of size. 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 small minority at large sizes. Carbonaceous II objects are 30-45% throughout. IIIB increases from 20 to 60%. Based on this data, most objects larger than 1 m are expected to be stony or cometary, in agreement with Table 1.

The objects from Table I are displayed on Fig. 1 according to their observed altitude of maximum brightness, which previous work has shown to be related to their fragmentation altitude, and their inferred strength in bars according to the I, II, and IIIB classifications of Table II. The objects fall into three groups: the stony Pribram by itself; the carbonaceous PN40503 through the Earth-grazing object; and the soft cometary Wurzberg through PN40401. Ideally, the objects should fall along the theoretical line from Eq. (7); in practice they exhibit several order of magnitude scatter. 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.

Impact pressure. The pressures in Fig. 1 are not corrected for entry velocity. Doing so provides a more precise measure of deviations from theory. For the entry velocities and brightness altitudes of Table I, Eq. (6) indicates that the velocity falls little by the altitudes of maximum brightness. Thus, the pressure depends little on size, and objects fragment at high altitudes where the pressure scales as $p \propto C_p V_0^2$. If an object's tensile strength is given by S , it fragments at altitude where $p \approx S/CV_0^2$, or

$$Z_f \approx -H \ln (S/CV_0^2). \quad (8)$$

Figure 3 shows the observed fragmentation altitude Z_0 vs the predicted fragmentation altitude Z_f for each of the objects in Table I, which can be identified by their altitudes of maximum brightness. There are now two groups of objects. The first, containing type I and II objects, is predicted to fragment at 35-45 km and is observed to fragment at 20-60 km. The second, containing IIIB objects, is predicted to fragment at 70-80 km and is observed to fragment at 60-90 km. In each case, the variance is wider in the observed fragmentation altitudes than in the predicted ones due to flaws in the larger objects, which reduce their effective strength, as discussed further in the context of the Russian analysis. Overall, there is an obvious correlation between Z_0 vs Z_f , with the diagonal running through the two groups. However, there is a great deal of spread from the correlation line within each group.

Breakup altitudes. The quantitative analysis of the EN-PN data is discussed in conjunction with the Russian analysis program, but some qualitative observations are in order. The 10 m daylight Earth-grazing object of 10 August is the largest object in Table I, but at magnitude -19, it is not the brightest by two magnitudes. That is because it was slower than other objects and remained at a higher altitude, where radiation is reduced in proportion to density. EN041274 (the Sumava event) was two magnitudes brighter because it was almost twice as fast, even though it was a type IIIB and broke up 15 km higher. PN40503 was one magnitude brighter

than the Earth-grazing object because it was faster and penetrated twice as deep. Conversely, EN170171 (Wurzburg) was two magnitudes dimmer than the Earth-grazing object because at 2.2 m it had only 5% as much area. PN39470 was also about 2 m, but was 50% faster. EN070591 (Benesov) struck vertically to a lower altitude. PN39121 was much dimmer because it was a IIIB that broke up at a very high altitude.

The remaining objects only span the interval from 1.8 to 1 m. EN070459 (Pribram) had magnitude -19 because it was stony and massive. EN010677 (Freising) was two magnitudes dimmer because it was carbonaceous and lighter. EN100469 (Otterskir) was another two magnitudes dimmer because it entered 40% slower. The carbonaceous PN39434 and MORP925 (G. Prairie) had comparable sizes, masses, and magnitudes. The 15 km lower altitude of PN39434 compensated for the two-fold higher velocity of G. Prairie. The soft cometary PN40401 and EN140863 had comparable sizes, masses, and magnitudes; the latter was distinguished by a greater angle of incidence. The trends in magnitude correlate reasonably well with measured velocities, altitudes, and trajectories and inferred size and strength parameters. However, each of these parameters is subject to dispute. The sizes are uncertain to factors of two; the masses to about an order of magnitude, and the strengths to a like amount. While the European and Prairie Network observations provide a useful data base for large objects, these uncertainties can only be addressed when the sensitivity of predictions to uncertainties in these parameters is assessed, as is done in discussion of the Russian analysis program.

Summary and conclusions. Earlier notes derived a model for the hydrodynamics, ablation, and radiation of meteor impacts at the level needed to infer meteor parameters from observations. The previous note compared that model to other U.S. models with different but related features and objectives. The most closely related model solves the same equations numerically, uses a consistent treatment of fragmentation, and produces similar results for common parameters, although it does not treat radiation in detail and assumes constant heat transfer coefficients. A second model differs primarily in its estimate of fragment spread velocities and variable heat transfer coefficients. Both are primarily concerned with interpreting the large Tunguska impactor, so they simplify many features and concentrate on varying parameters such as heat of vaporization and material strength to try to match observed surface damage patterns. The previous note discussed models with zero-dimensional hydrodynamics, simplified radiation transport, constant heat transport, parametric fracture and spread, and limited recourse to the limited data on objects tens to thousands of meters across.

This note extends that discussion to European data and models of meteor impact. U.S. analyses have used simplified models to try to achieve agreement with the very limited data on large objects while the European efforts have used more complex models that use observational data more directly to achieve agreement for a larger body of data on smaller objects. While the

former is at a level of simplification better suited to the model for data inversion needed for this effort, the latter represent a more thorough test of model sensitivities and uncertainties for objects in the size range of interest. Thus, it is also a useful test of the inversion model. Fortunately, as shown below, in cases of mutual applicability, the U.S. and European models appear to give broadly consistent results. This note puts the inversion model into a form appropriate for interpretation of the European and Prairie Network observations of 14 objects larger than 1 m in diameter. Over the last 35 years, the average rate of impact of such objects is about 0.4/yr, smaller for larger objects. The EN and PN observations use largely consistent classifications of these objects into stony, carbonaceous, and cometary materials. EN and PN observations indicate that most objects larger than 1 m are expected to be stony or cometary.

When these objects are displayed according to their observed altitude of maximum brightness, which is related to fragmentation altitude, and inferred strength in bars, they fall into three groups: one stony object, the carbonaceous objects, and the soft cometary objects. Ideally, they should fall along the theoretical line of pressure versus altitude, but in practice they exhibit several order of magnitude scatter due to variations in material strength. Correcting pressure for entry velocity provides a more precise measure of deviations from theory. Observed versus predicted fragmentation altitude indicates two groups of objects. Type I and II objects are predicted to fragment at 35-45 km and are observed to fragment at 20-60 km. IIIB objects are predicted to fragment at 70-80 km and are observed to fragment at 60-90 km due to flaws in the larger objects, which reduce their effective strength. There is a strong correlation, but there is a great deal of spread within each group.

The quantitative analysis of the EN-PN data is better discussed in conjunction with the Russian analysis program, but some qualitative observations are useful. The change in magnitude of the 14 large objects with size and speed can be explained readily by the changes in their size, speed, trajectory, and type. Trends in magnitude correlate reasonably well with measured velocities, altitudes, and trajectories and inferred size and strength parameters. However, each parameter is subject to dispute. The sizes are uncertain to factors of two; the masses to about 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 can only be addressed when the sensitivity of predictions to uncertainties in these parameters is assessed.

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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 Table 2)

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
$\cos z_R$	≈ 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	2.11
e	0.390 0.363	0.76	0.64	0.62	0.71	0.619	0.71
q [AU]	1.0127 0.9369	0.471	0.722	0.901	0.613	0.9246	0.597
Q [AU]	2.31 2.006	3.5	3.3	3.8	3.7	3.93	3.6
ω [deg]	355.6 315.76	282.0	73	321.0	265.1	218.65	86.5
Ω [deg]	317.956 317.949	251.78	16	116.75	259	46.314	95
i [deg]	15.22 6.93	2.3	12.6	2.71	0.8	23.70	5.4
type	(II)	IIIB	II	IIIB	II	II	IIIB
note	infrared tracking	4 GS				2 GS	
		28-5 Å/mm				67-22 Å/mm	
number	EN070459	EN 010677	EN100469	PN39434	MORP 925	PN40401	EN140863
name	Prábram	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

p vs z; cos the PN & EN w/o x

Fig. 1. Pressure vs altitude for diameters indicated and PN-EN data for objects > 1 m.

Fig. 2. Relative numbers of meteoroids of three basic types plotted against size d
 (Source: Ceplecha Fig. 2)

Zobs vs Zpred; PN & EN

Fig. 3. Observed vs predicted fragmentation altitudes.