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COMPARISON WITH RUSSIAN ANALYSES OF METEOR IMPACT

Gregory H. Canavan

The inversion model for meteor impacts is used to discuss Russian analyses and compare principal results. For common input parameters, the models produce consistent estimates of impactor parameters. Directions for future research are discussed and prioritized.

Earlier notes^{1,2,3} have derived a model for the hydrodynamics, ablation, and radiation of meteor impacts at the level needed to infer meteor parameters from observations⁴ and compared it to other U.S. models with related features and objectives⁵ and with data from European observational networks.⁶ Closely related western models^{7,8} solve similar equations numerically, use consistent treatments of fragmentation, and produce similar results for common parameters. However, they do not treat radiation in detail and only treat heat transfer parametrically. They are primarily concerned with interpreting the large Tunguska impactor, so they simplify many features and vary heat of vaporization, material strength, and other parameters to match limited surface damage observations. More detailed Russian analysis provides a mechanism to assess sensitivity to these simplifications.

Previous notes discussed models with zero-dimensional hydrodynamics, simplified radiation transport, constant heat transport, parametric fracture and spread, and limited use of the limited data on objects tens to thousands of meters across. This note extends that discussion to Russian models with one-, two-, and three-dimensional hydrodynamics, more careful treatments of opacities and radiation transport, detailed heat transport, measurement-based fracture models, extensive analysis, and explicit use of data on the impact of centimeter to meter meteors.

U.S. analyses have used simplified models to try to achieve agreement with the very limited data on large objects while Russian 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 level of simplification is better suited to the data inversion model, 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 Russian models give broadly consistent results.

The main subjects in the Russian analysis are Absorption Coefficients, Ablation Rates for Large Meteoroids, PN Bolide Characteristics, Ablating Piston Model, Benesov Bolide, SN Bolide Parameters, Sumava Event, Modeling Experiments, Modernization of Meteor Theory, and Proposals for Future Research. Absorption Coefficients have been produced and made available to the west for most of the constituents of the major impactors. Insensitivity of

transport to refinements suggests that no further development is needed for metric interpretations. Ablation Rates for Large Meteoroids have been studied less. Heat transport to the surface and ablation rates saturate due to self-shielding for impactors larger than about 1m. The impact of this shielding can be accounted for by using the correct ablation coefficient for the fragmentation altitude, but that is complicated by the observation that "chunking" of ablative material, which permits the removal of material for an energy less than the bulk heat of ablation of the material.

PN Bolide Characteristics have been used to normalize theoretical calculations for SN interpretation. Agreement between the PN and Russian masses is characterized as adequate, but discrepancies between photometric and inferred masses lead to large uncertainties in the interpretation of PN sizes. Calculations produced either unphysically low estimates of bolide density or high ablation rates—roughly a factor of 4 higher than expected—for objects $\ll 1$ m. The Ablating Piston Model is an important tool in the Russian analysis. Its predicted flow fields have been used to study ablation, equation of state, opacity, radiation transport, and wake temperatures. It is possible to concentrate on the radiation that comes from the hot, overdense object itself or to treat the combined object and wake, which contains all of the energy but involves a number of additional uncertainties. The inversion model has chosen the former route; the Russian analysis attempts the latter.

The Benesov Bolide has been studied repeatedly because it is an example of an observed impact that exhibits both high altitude breakups and penetration deep into the atmosphere. It is possible to achieve reasonable agreement between pancake models and observations, but they are clouded by order of magnitude uncertainties over masses. There does not appear to be a consistent set of assumptions that give the shape of the light curve and the mass of the object simultaneously. SN Bolide Parameters have been interpreted with pancake models normalized by PN and EN. The altitude of maximum brightness correlates well with the predicted fragmentation altitude from the inversion model, which is rederived above. The Sumava Event is the brightest impact observed by EN. It exhibits signs of nonequilibrium processes. Russian modeling does not capture the structure of the light curve at very high altitudes, but does accurately predict the magnitude and width of the main radiation pulse.

Modeling Experiments would be useful because the velocities needed are factors of 4-6 larger than those available in the laboratory and the scaling of transport and fracture mechanisms is not known. The Russian program has proposed to overcome those limitations by using large explosive generators to produce very high velocity plasmas in large vacuum chambers. Modernization of Meteor Theory is appropriate in that zero- and one-dimensional ablative piston model calculations are valuable for survey calculations of sensitivity to transport mechanisms, but cannot capture the geometry of fragmentation and dispersal.

From the perspective of inversion models, the non-equilibrium effects appear secondary, radiation efficiency would be difficult to improve because of the complicated geometries, evolution of debris clouds appears to be modeled about as well as the data, and high-velocity jets are unproven. For impacts below 60 km, the Russian program indicates that more work is needed on opacities, an improved ablative piston model for Benesov, three-dimensional hydrodynamics, cross checking of codes, and calibration of sensors. From the perspective of inversion models, opacities are adequate, improved ablative piston model for Benesov would be very useful—particularly if used in the west as well. Three-dimensional hydrodynamics codes appear premature, given that the principal uncertainties do not appear to involve dimensionality. Cross checking of codes is of interest—particularly with inversion codes—and calibration of sensors is a desirable, but apparently difficult undertaking. They would be particularly useful if correlated inversion codes, which could be an appropriate subject for future research.

Review of inversion model. Earlier notes developed a model for objects that ablate and fragment during entry,⁹ which also provides a common framework for the discussion of the European and Russian 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 zenith angle. 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, which is the essence of the inversion model. 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

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

The pressures for all 14 objects larger than 1 m in the European and Prairie Network (EN and PN) impact observational networks^{10,11} are within a factor of two above 20 km, where they scale as $p \approx C_p V_0^2 \sim \rho$. Pressure increases exponentially with ρ , so the fragmentation altitude of large objects is insensitive to the precise value of their material strength, which is poorly known. For large objects, the peak pressure is larger at lower altitudes because they do not decelerate until $\rho \approx \beta/H \sim D$. Smaller objects decelerate and produce lower pressures. For reference, the nominal yield stresses for iron, stone, carbon, and comet materials are 1,000, 100, 10, and 1 bar.¹² 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.

For the entry velocities and brightness altitudes of the > 1 m PN and EN objects, 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 objects tensile strength is given by S , it fragments at altitude where $p \approx S/CV_0^2$, or

$$Z_{\text{frag}} \approx -H \ln (S/CV_0^2). \quad (8)$$

The observed fragmentation altitude Z_0 can be identified with its altitude of maximum brightness. 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.

The Russian analysis program is based on analytic and numerical models with one-, two-, and three-dimensional hydrodynamics, detailed radiation and heat transport, empirical fracture models, and extensive analysis and use of data on the meteor impacts. It attempts to provide fundamental treatments of each adequate for the interpretation of the EN, PN, and U.S. satellite network (SN) observations. The program has been executed in collaboration with the west since 1994 and has produced a number of reports. Rather than trying to summarize each, it is more practical to start with the recently released final report,¹³ discuss its main conclusions, and use them to guide the discussion of earlier reports. The main topics in the final report are Absorption Coefficients, Ablation Rates for Large Meteoroids, PN Bolide Characteristics, Ablating Piston Model, Benesov Bolide, SN Bolide Parameters, Sumava Event, Modeling

Experiments, Modernization of Meteor Theory, and Proposals for Future Research, which are discussed in that order.

1. *Absorption Coefficients.* The Russian analysis program has produced and made available to the west a large library of opacity tables for most of the constituents of the major impactors, including iron, H-, LL-, C-chondrite vapor, cometary mater, water, and air for a wide range of densities and temperatures.¹⁴ While there are few experimental comparisons, observations indicate good correlation with line positions, strengths, and shapes, apart from some discrepancies discussed below. Those tables have gone through several iterations. Although newer data show changes that are significant for the interpretation of spectra from high altitude radiation, they indicate relative insensitivity of radiation and heat transport to detailed structure.

2. *Ablation Rates for Large Meteoroids.* Russian calculations indicate that heat transport to the surface and ablation rates saturates due to self-shielding for impactors $> 1\text{m}$.¹⁵ The radiation mean free paths from the previous effort are on the order of 0.1-1 cm at 0.5-2 eV and 10-100 bar for all materials but water. These lengths are greater than the dimensions of most objects of interest; thus, heat must diffuse in and radiation must diffuse out through the shock heated layer. For iron and water objects at 20 km/s at 15 km the reduction in heat transport coefficients is about a factor of 4; for other substances it is about a factor of 2. Mass loss rates are reduced accordingly.

This reduction is intermediate between the approximation of ignoring shielding,¹⁶ and assuming that the heat transport coefficient is inversely proportional to density, which gives a mass loss rate independent of density and temperature.¹⁷ It is roughly consistent with the estimates of the optical thickness of 1-10 m bodies performed for the inversion model.¹⁸ Unfortunately, Russian point calculations at 1 and 10 m do not provide insight into how the transport coefficients vary in the 0.5-4 m region of concern for the most frequent impactors. It is clear that shielding must be included in treatments of objects tens of meters across; it is not clear that it must be included in treatments of smaller objects.

This discussion is complicated by the observation that "the surface of real cosmic bodies is rather rough and other types of mechanically induced ablation may occur, i.e., removal of small parts of a meteoroid weakly bound with the main body..." This refers to the result familiar from reentry experiments that "chunking" of ablative materials may permit the removal of material for an energy less than the bulk heat of ablation of the material. This phenomenon, which was treated only phenomenologically in reentry studies, is an important effect that is discussed further below.

3. *PN Bolide Characteristics.* Prairie Network (PN) bolides are an important source of trajectory information and calibration for Satellite Network (SN) interpretation.¹⁹ The Russian effort reanalyzed some of the largest bolides discussed in the previous note²⁰ using PN light

curves, velocities, and zenith angles together with theoretical calculations with the "ablating piston" (AP) model discussed in the next section to infer the "radiating radius" of the object from its measured magnitude. Results are shown in Table I, which gives the PN number, the mass inferred from PN photography, Ceplecha and "our" (Russian) analysis of the extent of fragmentation, degree of agreement, pressure, adjusted PN masses, and Russian analysis masses, which range from 1 to 1,000 kg. The agreement between the PN and Russian masses are characterized as "in average—about 1.5-3 times," but the discrepancies between photometric and inferred masses are more than an order of magnitude—both ways—leading to large uncertainties in the interpretation of PN sizes. There is agreement on the mass of some objects such as PN40590 (Lost City), although there is disagreement on the peak radiation even for them.

Several versions of the AP model were used to study sensitivity to fragmentation and various other physical processes. The former showed that the light curves could be matched by plausible amounts of fragmentation but that the amount of fragmentation assumed was not uniquely determined. The latter showed that straightforward AP calculations either produced unphysically low estimates of bolide density or required high ablation rates, which was again attributed to the enhanced erosion or chunking discussed in the previous section. Roughly a factor of 4 increase in the ablation parameter was required to match both light and density measurements;²¹ however, in this case the increase is applied to objects $\ll 1$ m, for which shielding is not expected. The resolution of these issues is unclear.

4. *Ablating Piston Models* are an important tool in the Russian analysis, which builds on the formal analogy between hypersonic two-dimensional flows and the time-dependent one-dimensional insertion of pistons into hypersonic flows.²² It permits simple predictions of the radial variation of flow fields at any axial position behind the shock. The model has been used to study a large number of ablation, equation of state, opacity, and radiation transport issues and to predict the temperature in the wake behind the bolide.

The temperature in the wake behind a 0.85 m, 20 km/s bolide at 40 km is shown in the top chart of Fig. 1. The air temperature is initially about 2.5 ev, falling to 1 ev immediately behind the bolide and 0.5 ev 1 km behind it. The temperature of the ablated vapor is initially about 1.25 ev, falling to about 0.6 ev immediately behind the bolide and 0.2 ev 1 km behind it. The brightness temperature follows the vapor temperature, suggesting that the hot air layer is optically thin and hence radiates weakly at this altitude.

The bottom chart shows the density of maximum brightness. Initially it is at the overdense nose of the bolide. At the back of the bolide it goes underdense, remaining so for several hundred meters. Figure 2 shows the integrated radiation from the object and wake as a function of distance from the nose. The fraction of energy deposited in the flow that is radiated builds rapidly to about 10% in the first 1-2 m and then grows slowly to about 15% in the next

kilometer. The fraction detected by satellite sensors, f_s , is generally about half of the total. That detected by the ground-based panchromatic sensors is about 80% of that detected by satellite sensors, totaling about the 5% radiation efficiency usually inferred by such sensors.

This result indicates an important bifurcation in the analysis. It is apparently possible to concentrate on the radiation that comes from the hot, overdense object itself, which contains only about 50% of the total energy, or to treat the combined object and wake, which contains all of the energy but involves a number of hydrodynamic, mixing, and low temperature opacities that are poorly understood. The inversion model has chosen the former route. The Russian analysis attempts the latter, with acknowledged uncertainties.

Figure 3 shows the variation of predicted spectrum with axial position. At the top station (0.1 m), the spectrum peaks at about 5 eV, corresponding to the ~ 2.5 eV temperature of the nose. By 0.6 m the peak of the spectrum drops to about 3 eV. By 6 m the peak shifts to about 2 eV, corresponding to the ~ 0.6 eV of the wake. These predictions cannot be confirmed fully, as the 0.5-1.5 eV air radiation is not fully measured by either the ground or satellite sensors, but the higher energy portion of the spectrum is measured, and comparisons with theory are discussed below.

Figure 4 shows Russian predictions of the rate of transfer of energy to flow, dE/dt , and heat transfer coefficient, C_H , for 0.85 and 2.8 m diameter objects at 20 km/s. dE/dt increases roughly as the product of object area and density; profiles are similar for the two sizes. C_H is roughly the same below 60 km for the two objects. It decreases about an order of magnitude between 60 and 25 km, and about a factor of 3 between 40 and 25 km, i.e., it has a scale height about twice as large as that of the density. Thus, in the region of maximum heat transfer, its scaling is roughly intermediate between treatments that ignore the variation of C_H ²³ and those that take it to vary inversely with density.²⁴ While C_H varies relatively slowly with altitude in the region of concern, it is probably important to use the correct value for the fragmentation altitude rather than the conventional value for above 50 km.

5. *The Benesov Bolide* has been studied repeatedly because it provides an example of an impact observed both by EN and the Satellite Network (SN) that exhibits breakups at 60, 35, and 25 km and penetration deep into the atmosphere.²⁵ It is thus hoped that it can shed light on the strength and fragmentation of carbonaceous objects at those altitudes. Figure 5 shows the intensity of the peaks at 35 and 25 km and also the growth of the inferred radiating radius from about 0.75 to 2 m during them. Figure 6 shows the comparisons of the observed (dashed) and predicted (solid) magnitudes for the whole body and wake (c) and the first 200 m of the wake (d). These magnitudes are predicted using the spectrum of tens and hundreds of kilogram fragments shown (a), which decelerate at the altitudes shown (b).

By integrating over the whole wake it is possible to achieve reasonable agreement on the magnitudes. However, there are uncertainties. The size and mass of EN070591 (Benesov) are estimated photometrically by the EN as 1.9 m and 7,500 kg.²⁶ Other estimates range from a "dynamic mass of 80-400 kg... photometric mass of 5,000-13,000 kg... and masses derived from the radiative radius at the altitudes of 60-80 km (8000-2000 kg)." This order of magnitude range in estimated masses makes the interpretation of Benesov largely a matter of inferring plausible combinations of parameters and degrees of fractionation.

Benesov has been interpreted with two versions of a "progressive fragmentation" model. The first assumes fragmentation into a few tens of particles that evolve independently. The second assumes fragmentation into a few tens of particles that move collectively behind a common shock wave. The second, which corresponds to western "pancake" models, is assessed to be "in better agreement with observations." An additional complication is that the fragments are not generally visible separately with the sensors used for these observations, so their presence and number can only be inferred. The results from the progressive fragmentation model give masses of about 2,000 kg, in reasonable agreement with those from the simple indirect model used to interpret the PN measurements in an earlier section.

The EN measurements included spectra of the object. At 60 km they agree well with the predicted spectra. However, Fig. 7 shows that the predicted continuum spectrum for a 0.85 m object at 20 km/s and 40 km is about an order of magnitude below that measured. That is explained by the fragmentation of the 1.9 m object at about 50 km into $\approx (1.9/0.85)^3 \approx 11$ objects of 0.85 m diameter, which fragment at about 25 km. In the 50-25 km interval, their incoherent addition would contribute the order of magnitude increase in intensity needed for agreement with Fig. 7. However, 0.42 m radius objects would have masses of $\approx 4\pi \times 2000 \text{ kg/m}^3 \times (0.42 \text{ M})^3 / 3 \approx 640 \text{ kg}$, which is much larger than the 100-200 kg objects assumed in Fig. 6a. That would give a total mass of $\approx 640 \text{ kg} \times 11 \approx 7,000 \text{ kg}$, which is at the upper limit of the various estimates presented. Thus, there does not appear to be a consistent set of assumptions that give the shape of the light curve and the mass of the object simultaneously. This can be normalized in inversion models, but is a topic for continuing study in more fundamental analyses.

6. SN Bolide Parameters. The Satellite Network (SN) observations contain a number of large impacts for which they provide quantitative light curves; however, with one exception (1 Feb 1994) they do not provide initial velocities. The Russian analysis²⁷ has repeated the comparison of the Hills²⁸ and Chyba²⁹ models for meteoroid growth after breakup, recovered the essential sensitivities discussed earlier,³⁰ and adopted a "pancake" or single particle model for interpretation of further SN events. The events investigated (SN88106-96096) are shown in Table II. The radiated powers range from a few GW/sr to a few TW/sr and the radiated energies

from a few tons to a few KT. The radiating efficiencies range from about 5 to 10%; thus, the inferred kinetic energies range from a few tens of tons to a few tens of KT.

Table III provides more detailed information on seven of the largest impactors, mostly thought to be stony and hence having strengths of ≈ 100 bar. The radiated energies and powers are measured; the heights, velocities, and masses are inferred from calculations. With the exception of the 40-50 km/s SN88106, which fragmented at 43 km, the other objects fragmented at 30-35 km, in rough accord with previous analyses.³¹ Figure 8 shows the observed altitudes of maximum radiation versus predicted fragmentation altitude. As expected, the former lie close to the latter, although it takes some time and altitude for debris growth to occur at these altitudes.

The correlation is reasonably good. Three objects—SN90274, 94307, and 91277—are predicted to fragment at 24 km; their maximum brightnesses are actually at 30, 30, and 33 km, respectively, presumably reflecting somewhat lower strength than that assumed. The first two are of comparable size and speed, the third is about a factor of six smaller. The largest object SN94032 is predicted to fragment at 29 km, but is actually brightest at 21 and 34 km (the 28 km shown is an average), indicating two successive or a progression of breakups. The smallest object, SN94350, is predicted to fragment at 36 km, but is brightest at 30 km. SN88106 and 94149 are both predicted to breakup at about 38 km, but have a 10 km difference in observed maxima, possibly due to the greater effective strength of the 10-fold smaller SN94149.

One expects the ratio of the radiated energy E_r to the maximum power P_m to provide a measure of the pulse duration. Figure 9 shows that these estimates are on the order of 0.3-0.7 s for large objects. The smallest, SN94350 at 0.01 KT has 0.1 s duration in accord with numerical estimates.³² Having used this approach to estimate the energies of observed impactors, the Russian analysis used it to determine the rate of impact of objects as a function of their size or energy. The results, roughly 16 events larger and smaller than 0.25 KT, are roughly consistent with cratering and observational data, as is the $N \sim E^{-0.9}$ falloff of frequency at larger energies.

7. *The Sumava* event has been analyzed extensively because at a magnitude of -21 it is the brightest impact observed by the EN. It is also interesting scientifically because at about 27 km/s at 65 km, it shows signs of nonequilibrium radiation effects, being opaque to lines but not to continuum. The Russian analysis modeled the event with a simplified version of the ablative piston model, treating the shock as supercritical in estimating the radiation flux to the surface. While the treatment does not capture the structure of the light curve from 80 to 70 km, it does accurately predict the magnitude and ≈ 2 km (≈ 0.2 s) width of the main radiation pulse at 67 km. The Russian analysis also used laser interaction experiments to calibrate the model, producing ratios of impulse to energy similar to those produced with lasers in the west.

8. *Modeling Experiments* for impacts are difficult because the velocities needed are factors of 4-6 larger than those available in the laboratory or field and the scaling of transport and

fracture mechanisms on object scale is not known. The Russian program has proposed to overcome those limitations by using large explosive generators, in which Russia has an acknowledged world position, to produce very high velocity plasmas in large vacuum chambers. Numerical calculations indicate that such experiments could simulate many impacts, particularly Sumava high-altitude types, but engineering details and costs are not yet available.

9. Modernization of Meteor Theory. The Russian program has been based largely on zero and one-dimensional ablative piston model calculations. While they are valuable for survey calculations to study sensitivity to transport and physical mechanisms, they cannot capture the geometry of fragmentation and dispersal accurately. Thus, it is proposed to perform two-dimensional calculations of vaporization dynamics and the flow of vapor around objects. Such models have been applied to Sumava and Benesov impacts, where they have clarified mechanisms for decreasing the effective heat of vaporization, which is required to achieve agreement between experiments and one-dimensional calculations.

Two-dimensional calculations have also been used to study the interaction of flow fields between objects, helping to understand the role of voids in altering the radiation emitted. It is suggested that treatments of turbulent mixing and diffusion could improve these descriptions. Such models could also be extended to two-dimensional ablating piston models for better treatment of transport phenomena. The nonequilibrium and more complete opacity data needed for such calculations have been prepared. While there appears to be "general agreement" between observations and simulations, "further development of theory and new observations are necessary to get better insight into atmospheric entry, including radiation emission."

10. Proposals for Future Research. For impacts above 60 km, the Russian program indicates that research is needed on 1. cometary objects to include non-equilibrium vaporization and radiation, 2. radiation efficiency, 3. evolution of debris clouds after deceleration, and 4. modeling of high-velocity jets. For impacts below 60 km, more work is needed on 1. opacities, 2. an improved ablative piston model for Benesov, 3. three-dimensional hydrodynamics, 4. cross checking of codes, and 5. calibration of sensors. Much of the effort in the Russian program in 1996-7 was devoted to Electromagnetic Phenomena Caused by Micrometeoroids.³³ Those signatures are not yet in a form suitable for integration with the optical signatures discussed above; thus, they are also appropriate subjects for future research.

Summary and conclusions. Earlier notes have 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.

This note extends that discussion to Russian analysis of European ground and U.S. satellite observations 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 level of simplification is 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 and hence also a useful test of the inversion model. In cases of mutual applicability, the U.S. and European models give broadly consistent results.

The main subjects in the Russian analysis are Absorption Coefficients, Ablation Rates for Large Meteoroids, PN Bolide Characteristics, Ablating Piston Model, Benesov Bolide, SN Bolide Parameters, Sumava Event, Modeling Experiments, Modernization of Meteor Theory, and Proposals for Future Research, which are discussed below in that order, with reference to comparisons with the inversion model.

Absorption Coefficients have been produced and made available to the west for most of the constituents of the major impactors. Insensitivity of transport to refinements suggests that no further development is needed for metric interpretations. More line information could be useful for spectral analysis, but thus far, attempts at spectral classifications of bolide types have been limited. Ablation Rates for Large Meteoroids have been studied less. It is now clear that heat transport to the surface and ablation rates saturate due to self-shielding for impactors larger than about 1m. It is clear that shielding must be included in treatments of objects tens of meters across; it is not clear that it must be included in treatments of smaller objects. It appears that the impact of this shielding can be accounted for by using the correct ablation coefficient for the fragmentation altitude, but that is complicated by the observation that "chunking" of ablative material, which permits the removal of material for an energy less than the bulk heat of ablation of the material, is required to achieve agreement with theory, as in earlier phenomenological reentry studies.

PN Bolide Characteristics have been used to normalize theoretical calculations for SN interpretation. Agreement between the PN and Russian masses is characterized as "1.5-3 times," but discrepancies between photometric and inferred masses are more than an order of magnitude, which leads to large uncertainties in the interpretation of PN sizes. Calculations produced either

unphysically low estimates of bolide density or high ablation rates—roughly a factor of 4 higher than expected—for objects $\ll 1$ m. For them, shielding is not expected; the resolution of this issues is not clear. It can be normalized in the inversion model, but must be addressed by more fundamental studies.

The Ablating Piston Model is an important tool in the Russian analysis. Its predicted flow fields have been used to study ablation, equation of state, opacity, radiation transport, and wake temperatures. It is possible to concentrate on the radiation that comes from the hot, overdense object itself, which contains only about 50% of the total energy but is relatively well understood, or to treat the combined object and wake, which contains all of the energy but involves a number of additional uncertainties. The inversion model has chosen the former route; the Russian analysis attempts the latter. Either should work. Their uncertainties are complementary.

The Benesov Bolide has been studied repeatedly because it provides an example of an observed impact that exhibits breakups at 60, 35, and 25 km and penetration deep into the atmosphere. It is possible to achieve reasonable agreement between pancake models and observations, but they are clouded by order of magnitude uncertainties over masses. There does not appear to be a consistent set of assumptions that give the shape of the light curve and the mass of the object simultaneously, but that can be normalized in inversion models.

SN Bolide Parameters have been interpreted with pancake models normalized by PN and EN observations. The principal observable, the altitude of maximum brightness, correlates well with the predicted fragmentation altitude from the inversion model, which is rederived above. The Russian analysis used inferred kinetic energies to estimate the rate of impact of objects as a function of size, or energy. The results are roughly consistent with cratering and observational data, as is the falloff of frequencies at larger energies.

The Sumava Event is of interest because it is the brightest impact observed by EN. It exhibits signs of nonequilibrium processes and opaque to lines but not to continuum. Russian modeling with a simplified ablative piston model that treated the shock as supercritical does not capture the structure of the light curve at very high altitudes, but does accurately predict the magnitude and width of the main radiation pulse at 67 km. The

Modeling Experiments would be useful because the velocities needed are factors of 4-6 larger than those available in the laboratory and the scaling of transport and fracture mechanisms is not known. The Russian program has proposed to overcome those limitations by using large explosive generators to produce very high velocity plasmas in large vacuum chambers. Numerical calculations indicate that such experiments could simulate many impacts, particularly Sumava high-altitude types.

Modernization of Meteor Theory is appropriate in that zero- and one-dimensional ablative piston model calculations are valuable for survey calculations of sensitivity to transport

mechanisms, but cannot capture the geometry of fragmentation and dispersal. Thus, it is proposed to perform two-dimensional calculations of vaporization dynamics and the flow of vapor around objects. For Sumava and Benesov impacts, such models have clarified mechanisms for decreasing the effective heat of vaporization, which is required to achieve agreement between experiments and one-dimensional calculations. Proposals for Future Research at high altitudes include cometary non-equilibrium vaporization and radiation, radiation efficiency, evolution of debris clouds after deceleration, and modeling of high-velocity jets.

From the perspective of inversion models, the non-equilibrium effects appear secondary, radiation efficiency would be difficult to improve because of the complicated geometries, evolution of debris clouds appears to be modeled about as well as the data, and high-velocity jets are unproven. For impacts below 60 km, the Russian program indicates that more work is needed on opacities, an improved ablative piston model for Benesov, three-dimensional hydrodynamics, cross checking of codes, and calibration of sensors. From the perspective of inversion models, opacities are adequate, improved ablative piston model for Benesov would be very useful—particularly if used in the west as well. Three-dimensional hydrodynamics codes appear premature, given that the principal uncertainties do not appear to involve dimensionality. Cross checking of codes is of interest—particularly with inversion codes—and calibration of sensors is a desirable, but apparently difficult undertaking.

Overall, the Russian analysis emphasis on absorption coefficients is useful but saturating, on ablation rates for large meteoroids is useful but not critical, on PN bolide characteristics is useful for normalization of inversion and other models. Work on the ablating piston model seems to have reached the limits of current prescriptions for physical transport and fracture processes. The interpretation of the Benesov bolide, SN bolides, and the Sumava event are appropriate as highly relevant to inversion. The proposed modeling experiments, modernization of meteor theory, and proposals for future research seem undefined. Opacities are adequate, non-equilibrium effects appear secondary, radiation efficiency is difficult to improve, debris clouds are modeled adequately, and high-velocity jets are unproven. An improved ablative piston model for Benesov would be very useful, particularly if it was used in the west as well. Cross checking of codes and calibration of sensors are a desirable but difficult undertaking. They would be particularly useful if correlated inversion codes, which could be an appropriate subject for future research.

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Table I

Source: Popova 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.

Assessment of kinetic energy of bolides E_0 using
theoretical values of integral efficiencies η_i
and detected energy of the light flashes E_r

Bolide data	P_m , W/sr	E_r , kt	η_i , %	E_0 , kt
88106	1.42E+12	1.79	10.7	15.9
90274	3.53E+11	0.57	9.7	5.88
91277	6.56E+10	0.14	8.4	1.66
93304 *	6.32E+09	0.0095	5.95	0.16
93333	1.05E+10	0.0063	5.58	0.11
94032	3.17E+12	4.39	11.5	38.0
94149	9.90E+10	0.090	8.00	1.12
94154	1.56E+11	0.12	8.26	1.45
94166 **	4.00E+09	0.0031	4.93	0.063
94227	2.71E+10	0.043	7.33	0.587
94265	6.50E+10	0.016	6.53	0.244
94281	2.20E+10	0.0157	6.51	0.241
94293	1.41E+10	0.021	6.68	0.314
94300	8.42E+10	0.077	7.86	0.979
94305	2.43E+11	0.36	9.26	3.87
94307	3.39E+11	0.56	9.67	5.79
94341	8.28E+09	0.0019	4.49	0.043
94347	1.13E+10	0.0029	4.87	0.059
94350	2.76E+10	0.0086	5.86	0.147
95002	7.50E+09	0.0071	5.79	0.123
95004	1.93E+10	0.044	7.35	0.598
95010	9.00E+09	0.006	5.63	0.106
95018	3.25E+10	0.022	6.72	0.327
95047A	1.50E+10	0.0042	5.21	0.081
95047B	1.00E+10	0.014	6.31	0.222
95092	1.20E+10	0.0060	5.63	0.106
95188	3.00E+10	0.0333	7.20	0.463
95190	6.20E+10	0.0595	7.73	0.770
95192	4.10E+10	0.031	7.13	0.434
95217	1.80E+10	0.0238	6.89	0.346
95218	2.40E+10	0.013	6.35	0.206
95229	1.60E+10	0.038	7.32	0.520
95236	2.70E+10	0.0286	7.06	0.405
95252	7.50E+10	0.119	8.36	1.420
95269	1.10E+10	0.0029	4.96	0.058
95274	2.10E+10	0.0083	5.93	0.140
95317	1.10E+10	0.005	5.47	0.091
95322	6.50E+09	0.0008	3.81	0.021
95323	5.50E+09	0.0024	4.79	0.050
95329	2.10E+10	0.0069	5.76	0.120
95343	4.70E+10	0.0286	7.06	0.405
95356	7.80E+10	0.107	8.26	1.297
95361	2.20E+10	0.083	8.03	1.04
96015	6.30E+10	0.067	7.83	0.851
96018	4.00E+10	0.0029	4.96	0.058
96046	2.00E+10	0.012	6.26	0.190
96047	1.70E+10	0.0076	5.85	0.130
96073	3.30E+10	0.055	7.65	0.716
96086	8.00E+09	0.002	4.64	0.044
96089	3.00E+10	0.021	6.77	0.309
96096	4.20E+10	0.0286	7.06	0.405

* - noisy,

** - Montreal, 10 Hz filtered, noisy, preliminary
estimates of the energy has been corrected.

Table III

Source: Nemtchinov Table 6.1

Parameters of SN events obtained from simulations using a single-body model

Event	E_r , kt	P_m , W/sr	h_m , km	E_0 , kt	M_0 , ton	V_0 , km/s	η , %	η_i , %	Probable composition
88106									
15 Apr. 1988	1.70	$1.4 \cdot 10^{12}$	43	8-9	25-45	40-50	18-21	11	stony
90274									
1 Oct. 1990	0.57	$3.5 \cdot 10^{11}$	30	3-5	70-200	15-20	11-19	9.7	stony
91277									
4 Oct. 1991	0.14	$6.6 \cdot 10^{10}$	33	0.9	20	15-20	15	8.4	stony
94032									iron
1 Feb. 1994	4.39	$3.2 \cdot 10^{12}$	34, 21	31	400	24*	14	12.5	stony
94149									
29 May 1994	0.090	$9.9 \cdot 10^{10}$	34	0.6-2.5	2-140	< 50	3.5-15	8.0	—
**94307									
3 Nov. 1994	0.56	$3.4 \cdot 10^{11}$	30**	3-5	70-200	15-20	11-19	9.7	stony
94350									
16 Dec. 1994	0.0086	$2.8 \cdot 10^{10}$	30	0.07-0.3	0.25-17	< 40	3.3-14	5.9	—

* - Entry velocity is known from observational data,

** - Using a similarity to 90274 in E_r , P_m and a shape of the light curves.

Here E_r is the energy of the radiation impulse, P_m is the peak power of radiation, h_m is the height of breakup, E_0 is the kinetic energy of the body, M_0 is the mass, V_0 is the velocity, η is the luminous efficiency and η_i is the integral luminous efficiency from approximation (6.6).

Fig. 1. Source: Golub Fig. 4.2

Maximal temperature of the air (T_{am}), of the vapor (T_{vm}) and brightness temperature in the panchromatic bandpass (T_{bm}) in the cross-section of the bolide versus distance along the axis Z (upper panel) and the ratio ρ_{bm}/ρ_H of the density ρ_{bm} at the point of maximum brightness to the atmospheric density $\rho_H = 4 \cdot 10^{-6}$ g/cm³ (lower panel).

Fig. 2.

Source: Golub Fig. 4.7

The fractions of the energy radiated in whole spectrum (f_t), in the SN sensors wavelength range (f_s) and in the panchromatic passband (f_p) as functions of distance Z for $H = 40$ km, $R = 0.42$ m, $V = 20$ km/s.

Fig. 3. Source: Golub Fig. 4.5

The model spectra at the altitude of 40 km for $R = 0.42$ m, $V = 20$ km/s, and different lengths Z of the luminous volume.

Fig. 4. Energy transfer rate to flow and heat transfer coefficients for 0.85 and 2.8 m objects at 20 km/s.

Fig. 5.

Source: Popova Fig. 5.1

The intensity curve and radiative radius
of the Benešov bolide

Fig. 6.

Source: Popova Fig. 5.2

Distribution fragments by mass at the breakup moments (squares - at 60 km altitude, stars - at 40-36 km) (a), deceleration curves (b) and light pulse (c, d) obtained in a frame of the progressive fragmentation model for meteoroid with $\rho = 2 \text{ g cm}^{-3}$, initial mass $M = 4000 \text{ kg}$, fragment masses are of about 2-8% of mass in breakup. Intensity curve integrated radiation from only 200 m after leading fragment (d). Light curve of Benešov is given by dashed line.

Fig. 7. Source: Popova Fig. 5.8

Comparison of the observed spectrum at altitude 40 km (thin line) and the model one (thick line) for meteoroid with $R = 0.42$ m ($H = 40$ km, $V = 20$ km/s).

Zo vs Zpred

Fig. 8. Observed vs predicted fragmentation altitude.

t vs Er

Fig. 9. Pulse duration versus radiated energy.