Title:

**METEOR SIGNATURE
INTERPRETATION**

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METEOR SIGNATURE INTERPRETATION

Gregory H. Canavan

Meteor signatures contain information about the constituents of space debris and present potential false alarms. Better models could both extract the maximum scientific information possible and reduce their danger. possible Accurate predictions can be produced by models of modest complexity, which can be inverted to predict the sizes, compositions, and trajectories of object from their signatures for most objects of interest and concern.

This note discusses the interpretation of the signatures of the meteors that frequently impact the Earth's atmosphere. Their optical signatures both contain information about the constituents of space debris and present potential false alarms to warning systems.^{1,2,3} Better models for impact signatures could both extract the maximum scientific information possible from them and reduce the danger of false alarms.^{4,5,6} The scientific benefits of the former are great, the societal benefits of the latter are incalculable. Given these significant dual payoffs, performing detailed scientific studies of both issues at the earliest possible date is highly desirable.⁷

Background. An earlier note studied the optical signatures produced by intact objects entering the Earth's atmosphere as a function of their size, speed, and angle of incidence, finding that it was possible to produce accurate predictions and correlations with data using models of modest complexity.⁸ Further work showed that the models involved were of such a nature that they could be inverted to predict the size and trajectory of an object from the magnitude and duration of the optical signature measured by a number of sensors. Subsequent investigation showed that this was the case not only for intact objects, but for important classes of objects that ablate or fracture during entry. The purpose of this note is to explore the range of parameters for which that inversion is possible.

Such an inversion would have a number of advantages, not the least of which is that it would readily lend itself to computer implementation. That is, it could be converted into a filter that could process wide-band sensor information in real time, by which it could automatically detect the events with the characteristics of meteor impacts, predict their sizes and trajectories, and support subsequent discrimination from missile or explosive signatures. Such filters could greatly reduce the false alarm rate from natural events as well as reducing the demands for subsequent manpower-intensive steps of evaluation. Thus, they could sort the signatures into those to be processed for scientific content and those that should be examined carefully for terrestrial origin.

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Context. This note is the first of a series that document the analysis that converts predicted meteoroid signatures into filters to estimate the size, speed, and trajectory of meteors from their wide-band signatures and further categorize them according to their thermal and mechanical strength. It should lead to significantly improved signature predictions and filters, support wide-band tests, and culminate in the implementation of real-time capabilities. There are natural opportunities for review of progress against scientific goals such as meteoroid signatures, and against operational goals such as filter probability of detection and false alarm rate—and to take corrective actions, should unforeseen developments require it. To fully address these scientific and technical goals is necessary to develop physical models of various mechanisms of meteor deceleration. In doing so, it has been found adequate to characterize meteors primarily by their heat of ablation and mechanical strength. The next section reviews that characterization.

Meteor parameters. Objects in space are called meteoroids. Those that enter the atmosphere are called meteors. Those that hit the ground are called meteorites. This study is primarily concerned with the last two, meteors and meteorites, since only they generate strong visible signatures. These two categories are sometimes loosely referred to as "objects" in the discussion below for simplicity and to avoid the term asteroid, which can imply that cometary objects are not of interest. The deceleration of and radiation from meteors depends primarily on their thermomechanical and mechanical strength. The former is largely characterized by the meteor's heat of vaporization; the latter by its tensile strength. Table 1 gives parameters for the conventional classes of meteors: iron, stony, carbonaceous, and cometary meteors:

Table 1. Approximate meteor parameters.

<u>type</u>	<u>density</u> (kg/m ³)	<u>Q</u> (J/kg)	<u>Strength</u> (N/m ²)
iron	8000	8x10 ⁶	10 ⁸
stony	3500	8x10 ⁶	10 ⁷
carbonaceous	2200	5x10 ⁶	10 ⁶
cometary	1000	2.5x10 ⁶	10 ⁵

Density varies by about an order of magnitude between metallic objects, which are largely iron, and cometary objects, which are largely water. The heat of vaporization, which determines how rapidly mass is removed from the object, only varies about a factor of four between iron objects, which are thermally the strongest, and cometary objects, which are the weakest. The tensile or yield strength, which determines how much pressure or stress an object can withstand before breaking up, varies much more—about an order of magnitude between each class of asteroids. Given these large variations overall, and the significant variations within each class of objects, it is appropriate to survey a wide variety of combinations of objects.

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The heat of vaporization largely determines how rapidly mass is removed from the object, because it determines the rate at which mass is removed for a given heat flux to the surface. Removal also leads to an important feedback loop. Ablation reduces the size and mass of an meteoroid, which increases its drag and deceleration. That increases its stress profile and probability of fragmentation. Reciprocally, fragmentation enhances ablation, because fragmentation produces smaller objects with more drag that decelerate more rapidly, which increases heat fluxes to the object.

Heat transfer rates are largely empirical; they are not known to better than a factor of two in this parameter regime. Thus, ablation can at best be treated at about that level of detail. The parameters governing it are phenomenological, and less reliable, particularly when the complicating effects of fragmentation are introduced. More complicated models could be attempted, but might not be more reliable, given the complexity of the phenomena and the lack of calibration of the process at the hypersonic speeds involved.

Tensile strength determines how much pressure an object can withstand before breaking up. There are a number of models of the process, but they all essentially reduce to the assumption or assertion that fragmentation occurs when the stagnation pressure on the front of the meteor exceeds its tensile strength. That breaks the meteoroid up into smaller pieces, each of which has more drag and hence decelerates faster. That causes a cascade through scales that persists until the fragments are small enough to move apart, develop bow shocks of their own, and decelerate independently. If the fragment decelerate to speeds at which stresses and ablation are reduced adequately, they hit the ground as meteorites.

Conceptually, fragmentation is calculable. In practice, it is an empirical process based on little knowledge of the key parameters involved. While density and heat of vaporization can be determined with some confidence, material strength cannot. It can only be inferred from impact measurements and meteorite fragments. The former give widely varying results, and the latter represent a biased sample of only those objects strong enough to reach the ground. Celestial measurements such as Shoemaker-Levy-9 give values consistent with little or no strength at all. Thus, an important product of the interpretation of meteor impacts on the atmosphere could be the inference of the strength of a wide class of objects, which would be of value both scientifically and for the planning of interaction experiments.

Entry processes. During entry, the dominant processes are deceleration, radiation, ablation, and fracture, in roughly increasing order of difficulty. The main processes and their key elements, dominant uncertainties, and rough impacts are described below.

Deceleration is the slowing down of the meteor as it passes through the upper atmosphere. Modeling the deceleration of intact objects is largely a matter of hypersonic flow and drag, which have largely been understood since Newton. Conceptually, that is a simple

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problem, but it is complicated by the irregularity of the meteoroid's shape, which makes the hypersonic solutions for spheres only an approximation, which is probably no better than about a factor of two. The phenomena can be described by models of varying complexity. Deceleration can initially be treated with corrections to the formula for the hypersonic slowing down of a sphere. If that is adequate, this complex flow problem can be reduced to a set of ordinary differential equations in which most of the physics is represented by a few dimensionless coefficients, which can be varied to assess sensitivity.

Radiation is perhaps the most complex of the processes and should probably be calculated in detail. It is an important process, although as a diagnostic rather than as a major energy conversion. At meteor speeds of 10 to 20 km/s, the temperature in the shock in front of the meteor is only about one to three electron volts ($\text{ev} \approx 11,600$ degrees), which is too low to radiate a great deal of energy, although the amount and spectrum can provide useful diagnostics information. However, taking advantage of it involves some complications, as the air and meteor material opacities are not known well in this temperature regime, which has led to order of magnitude discrepancies in the interpretation of radiated power, some of which still persist.

Radiation is difficult to treat accurately in the few-electron-volt temperature regime of meteor impacts, but is the principal diagnostic there, as little else is usually measured. Zeldovich and Raiser's classic treatment of opacity and radiation was intended for higher densities and temperatures.⁹ U.S. extensions to lower temperature air are now dated and discontinued. Opacities have been revised for meteoroid conditions by Biberman and Nemchinov,¹⁰ but their treatment gives significant uncertainties for temperatures of a few electron volts and for densities of shocked air at 10-30 km, where most radiation takes place. It is likely that the order of magnitude discrepancies in the radiating efficiency attributed to recent impacts can be traced to these issues. If so, improved opacities and models of radiation flow and cooling are available to improve physical models to any extent required.

Since radiation is not the dominant energy loss mechanism, and it enters signature generation passively, it can be treated to first order through a two-state opacity i.e., one that is opaque at short wavelengths and transparent at long wavelengths, to estimate the impact of opacities on meteor signature and sensitivity. However, if necessary, it should be possible to improve the radiation loss model¹¹ by analogy to treatments of the propagation of laser supported waves^{12,13,14} to any order required.¹⁵

Ablation is understood almost as well as drag for intact objects, although the heat flux to the meteor surface is complicated by the irregular surface, which disturbs the transitional or turbulent flows. If fragmentation occurs, these complications are compounded by the resulting smaller objects and interacting flow fields, although these are by themselves only factor of two complications.

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Fragmentation. There are competing descriptions of the coupled ablation and fragmentation process that occur during meteor entry in this literature. The treatments due to Hills and Goda,¹⁶ Chyba, et. al.,¹⁷ and Nemchinov, et. al,¹⁸ incorporate different physics, have different equations, and can give quite different results in regions of interest. Comparisons should be able to resolve their theoretical differences. However, the models depend strongly on the strength of the meteors, which is not known accurately. It is not known how strongly these empirical uncertainties influence observables, but preliminary analysis indicates the sensitivity is less than would be expected *ab initio*.

Fragmentation should be treated with detailed two-dimensional calculations, but attempts to do so have this far not been particularly enlightening. To achieve agreement with even the modest data base on fragmentation is has been necessary to postulate preexisting fracture patterns in the objects that are not measurable and to assume strengths of bulk materials that are not measured.¹⁹ Thus, this study will emphasize tests of sensitivity to asymmetries, which will be performed parametrically within the scaling of the three developed models discussed above. The emphasis will be on the identification of trends that can be modeled simply and that are sufficiently robust to survive the inversion process.

Association of properties and processes. The physical properties of the various meteors are roughly correlated with their types as shown in the left columns of Table 2. For example, metal objects are thermally hard and mechanically strong; cometary objects are soft and weak. This correlation also implies certain associations between the dominant processes for the different classes of meteors. Metal objects are generally sufficiently hard and strong to decelerate before they break up, carbonaceous objects ablate and then break, stone objects break and then ablate, and cometary objects do both very quickly.

Table 2. Combinations of processes.

		<i>mechanical strength</i>		<i>processes</i>	
		<u>strong</u>	<u>weak</u>	<u>strong</u>	<u>weak</u>
<i>thermal</i>	<u>hard</u>	metallic	carbonaceous	decelerate	ablate, break
<i>strength</i>	<u>soft</u>	stony	cometary	break, ablate	break, ablate

These associations are not precise. Whether deceleration, ablation, or fracturing comes first depends on the precise values of the object's parameters, but his table indicates the rough order of likelihood. Since it is generally simpler to treat one process rather than several, strong, hard objects that neither ablated nor fractured, i.e., metal meteors, were treated in the previous note. The sections below and the subsequent notes address the other combinations in rough order of

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increasing complexity, i.e., objects that ablate with out fragmentation, e.g., stone; those that ablate and fracture, e.g., carbon; and those that break and then ablate, e.g., comets.

This progression in processes suggests a logical plan of attack for the discussion, derivation, and testing of the phenomenology models and filters. Accordingly, the subsequent papers address these meteor classes and processes in a progression from those that provide the simplest models and filters to those that require the most complex analyses. According to Table 2, that progression moves from metal objects that decelerate with little ablation or breaking, for which radiation can be studied in a simple context. The next step is intact carbonaceous objects that ablate significantly. Then stony objects that break readily. And finally cometary objects which do both at high altitudes. The remaining papers in this series derive the models for each of these interactions, explore their sensitivities, provide predictions of observables, invert the models to provide meteor properties in terms of observed signatures, and combine them into an overall model that discriminates on meteor class as well.

Models. The above discussion of the degree of simplification possible in the treatment of each of the main physical phenomena indicate that it is possible to construct models that combines those processes at a consistent level of accuracy, which can be run quickly on modest computers. Such a model can then be exercised to study the sensitivity to the main impact parameters—mass, velocity, composition, angle of incidence, etc.—as well as the parameters describing the uncertain phenomena discussed above. Those results can then be compared with an appropriate subset of the impact data to select the unknown parameters. That done, the model could be exercised with those parameters to generate predictions for comparison with the rest of the data to test consistency. Such a model was derived, discussed, and compared with limited observational data in a previous paper.²⁰

Such calculations would be useful in establishing the sensitivity of radiance profiles to these parameters. However, even if the final results are not overly sensitive to these parameters, the calculations would still cover a very large phase space. Thus, the next objective is the reduction of the size of that phase space to a manageable number of dimensions by the elimination of variables to which the results are insensitive. That is where simple but robust models of each of the energy conversion process are important.

However, for this effort, the principal value of a model is that so long as it is physically sound, it will produce physically real signatures. If the model is inverted to produce a filter in a conservative manner, whatever real observations that are provided to it should produce masses, compositions, velocities, compositions, and incidence angles that are physically realistic as well. That property is not the case with empirical correlations or approximate inversions of numerical models. This step—ensuring realizability of the inferred meteor parameters—does not appear to have been attempted by treatments in the literature. Its ultimate success depends on the degree to

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which the number of parameters, i.e., the dimensionality of the parameter space, can be reduced by survey calculations and comparisons. The earlier report indicated that such an inversion should be possible at least for meteor parameters of interest. The results of the papers in this series indicate that to be the case with even more general conditions.

Summary and conclusions.

This note discusses the interpretation of the signatures of meteor impacts on the Earth's atmosphere, which contain information about the constituents of space debris and present potential false alarms. Better models for impact signatures could extract the maximum scientific information possible from them while reducing the danger of false alarms. Earlier work showed that it was possible to produce accurate predictions and correlations with data using models of modest complexity. Further work showed that the could be inverted to predict the size and trajectory of object from the magnitude and duration of their measured optical signatures—not only for intact objects, but for important classes of objects that ablate or fracture during entry.

The deceleration of and radiation from meteors depends on their thermomechanical and mechanical strength. The former is roughly known; the latter is not in practice. Lack of data on meteor tensile strength is a key question that these filters could address. The main entry processes are deceleration, radiation, ablation, and fragmentation. All but radiation impact the energy budget in an important way, and radiation is the most important diagnostic. Deceleration and ablation are understood to within roughly factors of two. Fragmentation is only understood to within about an order of magnitude because of limited knowledge about the object's mechanical strength. This is not a matter of models versus fundamental calculations; the information is not in hand to fully calibrate either. Measurement of the fragmentation of meteors is perhaps the best way to resolve questions about the strength of space objects.

The progression in processes provides a logical plan of attack for the models and filters, which is used in subsequent papers: metal objects that decelerate with little ablation or breaking, carbonaceous objects that ablate significantly, stony objects that break readily, and cometary objects that do both. The principal value of these models is that they are physically sound, so they produce physically real signatures. Thus, when inverted conservatively, any observations provided to it should produce meteor estimates that are physically realistic as well, which is not the case with empirical correlations or approximations. Results to date indicate this level of accuracy and realizability should be maintained for all meteors of interest.

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