LA-UR-01-5647
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BOLIDE DYNAMICS AND LUMINOSITY MODELING: COMPARISONS BETWEEN UNIFORM BULK DENSITY AND POROUS METEOROID MODELS

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ABSTRACT

We compare predictions of bolide behavior using basic meteoroid models, first assuming a uniform bulk density throughout the body and secondly assuming a uniform chondritic composition throughout, but with varying amounts of porosity (assumed to be filled with either water-ice or open space). The second model is based one the uniformity of spectral observations over many years from shower meteors from the extremes of the Geminids to the dustball-like Draconids. The first model utilized is due to ReVelle (1979, 1993) and the second is based upon the porous meteoroid model of ReVelle (1983, 1993). The standard, uniform bulk density model assumes that the drag and heat transfer area are equivalent in the positive, shape change factor limit. For porous meteoroids however, the heat transfer area can exceed the drag area by increasingly larger amounts as the body's porosity increases. ReVelle (1983) used this approach to show that the bulk density and ablation parameter compositional group identifications of Ceplecha and McCrosky (1976) were essentially correct. When these factors are introduced into the relevant model equations, a set of nearly self-consistent predictive relations are developed which readily allows comparisons to be made of the end-height variations and of the normalized luminous output of the two basic meteoroid models.

1. INTRODUCTION AND OVERVIEW

1.1 Uniform versus porous meteoroids:

Spectral measurements of shower meteors taken over many years indicate nearly chondritic abundances for all showers from the Geminids to the Draconids regardless of their inferred bulk density or overall strength. This indicates that one way of accounting for atmospheric behavioral differences, i.e., bolide types, is to assume varying degrees of porosity (but are the pore spaces filled with water-ice or something else or just empty?) In this paper, we will model bolides both ways and determine which approach best agrees with the observed data (dynamics and luminosity).

1.2 Normalized or un-normalized light curves:

We have separated the light emission into the product of a unit normalized light curve as a function of either height or of time and a height, velocity, mass and wavelength dependent luminous efficiency. The emission is un-normalized by taking the product of these two quantities and the maximum time rate of change of the kinetic energy over a specified electromagnetic wavelength band. We have not completed this part of the work yet so here we will only summarize previous work that has already been done on this topic. We will report on this separately later next year at the Berlin ACM Conference (July, 2002).

2. FUNDAMENTAL METEOROID MODELING

2.1 Uniform bulk density models versus porous meteoroid models:

Uniform bulk density models arise from the definition, $\rho_m \equiv m/V_o$, with the shape factor, $S_f \equiv A_d/V_o^{\,2/3}$, where A_d is the drag area (of the frontal cross-section) and V_o is the total volume.

Porous, meteoroid modeling can be summarized by noting that the heat transfer area, A_h, increases in direct proportion to the relative degree of porosity, ψ' = porous volume/total volume ($0 \leq \psi' \leq 1$), with the result (ReVelle, 1983) for porous meteoroids:

$$\mathbf{A_h = A_d \cdot (1- \psi')^{-1}}$$
$$\mathbf{\rho_m = (1-\psi')\, \rho_{mo} + \psi'\, \rho_m^*}$$

$$\mathbf{A_h = A_d \text{ if } \psi' = 0: \text{Uniform bulk density limit}}$$

where

ρ_{mo} = bulk density of nonporous chondritic materials
ρ_m^* = bulk density of porous materials with the constraint that:

$$0 \leq \rho_m^* \leq 1.0 \text{ g/cm}^3$$

using the water-ice density and empty space (vacuum) as upper and lower limits of the pore space density respectively.

$$\mathbf{\sigma^* = \sigma \cdot \{A_h/A_d\}}$$
$$\mathbf{\sigma^* \cdot \rho_m = \sigma \cdot \rho_{mo} = \text{constant} = 7.4 \cdot 10^{-12} \text{ (CGS units)}}$$

At V_∞ = 20 km/s for porous meteoroids:

$$\mathbf{\log(\sigma^* \cdot \rho_m) = -11.13}$$

2.2 Interpretation of bolide groups

From Ceplecha et al. (1998) using a uniform bulk density bolide model and averaging over all bolide groups (with ±1 stnd. dev. term included):

$$\mathbf{\log(\sigma^* \cdot \rho_m) = -11.183 \pm 9.91 \cdot 10^{-2}}$$

This can be compared directly to the result above for porous meteoroids. The excellent agreement between these two independent evaluations makes porosity a very viable explanation of most bolide behavior if bolides are actually both porous and chondritic. The advantage of this approach is that as porosity→0, the two models produce identical results.

3. LUMINOSITY MODELING OF BOLIDES

3.1 Normalized and un-normalized bolide light curves

Assuming that the light emission, I over an electromagnetic wavelength band is proportional to the time rate of change of the kinetic energy, dE_k/dt, of the body (where the proportionality constant is τ, the luminous efficiency of a chondritic substance of uniform bulk density) over that wavelength band.

$$\mathbf{I = -\tau \cdot dE_k/dt}$$

$$\mathbf{dE_k/dt = -0.50 \cdot V^2 \cdot dm/dt \cdot \{1+\Delta(z)\}}$$
$$\mathbf{dm/dt = \sigma V \cdot dV/dt = -0.50 \cdot \rho V^3 \sigma (A_h/m)}$$
$$\mathbf{\Delta(z) = 2/(\sigma V^2)}$$
" = inverse dimensionless ablation efficiency at any height

Assume τ = constant and normalizing the light by I_{max} to have unit amplitude, where I_{max} is the value of the maximum theoretical light emission. In our approach, we have allowed ρ, V and σ to vary with time/height unlike the classical approach (Bronshten, 1983) that has only allowed ρ as a variable.

$$\mathbf{\therefore I_L / I_{max} = \Psi(t) \cdot \tau_c}$$

$$\mathbf{I_{max} \propto \rho_{max} \cdot V^5_{max} \cdot \sigma_{max} \cdot \{1+\Delta_{max}(z_{max})\}}$$

where

$$\mathbf{\Psi(t) = -dE_k/dt / I_{max}}$$
" = the theoretical light curve shape versus time.

To obtain the actual light emission in absolute power units over a specific wavelength interval, we must calculate τ_L from first principles. It is expected that $\tau_L = f(\rho(z), V$, composition, body size, Knudsen number, etc.).

3.2 Effects of $\mu < 0$ on the emission of light:

An expression due to Levin and presented in Bronshten (1983) for the standard light curve as a function of the μ parameter (for details see ReVelle, 2001d) :

$$\mathbf{I \equiv dm/dt/(dm/dt)|_{max}}$$

$$\mathbf{I = I_{max} \cdot \{\mu^{-\mu/(1-\mu)}\} \cdot \{\rho/\rho_{max}\} \cdot [1-(1-\mu) \cdot \{\rho/\rho_{max}\}]^{\mu/(1-\mu)}}$$

This formula was derived from classical meteor theory for an isothermal, hydrostatic atmosphere, assuming that:

$V = V_\infty$ = constant, σ = constant, μ = constant

Its range of applicability should be small for large, bright bolides where air drag is significant. Also, for large negative μ, drag is even more important and the formula is even less likely to be useful. Its solutions become imaginary, however if $\rho/\rho_{max} < 1$.

We have also derived a new, generalized light curve model with "gross-fragmentation" break-up (used below) with ρ, V, and σ as variables (to be submitted shortly). Details will be presented at the Berlin ACM Conference in July of 2002.

As shown by ReVelle (1999, ACM, and 2001d-this conference), it is not a sufficient condition for μ to be < 0 to have significant effects that would invalidate the single-body approximation. It is also necessary that $H_f << H_p$. After fragmentation starts, the effective Q_i will also decrease (and σ will become larger) which will also influence this progression of events.

4. APPLICATIONS: THE TAGISH LAKE METEORITE FALL: JANUARY 18, 2000- SOME PRELIMINARY RESULTS

Below we summarize some of our preliminary results for the Tagish Lake bolide. This is given below for the case of μ = 0.10 = constant. We also present results in Table 2 at the end of this paper for the case of μ = 2/3 (no shape change).

4.1 Fixed bolide entry parameters:

1. V_∞ = 15.8 km/s, θ = 18 °, S_f = 1.209 (sphere initially), $Q_{vap} = 7.98 \cdot 10^6$ J/kg , $Q_{melt} = 1.884 \cdot 10^6$ J/kg
2. $k_1 = 5$, $k_2 = 25$, $Re_{trans} = 9 \cdot 10^5$ (at the turbulent boundary layer transition)
3. $8.0 \cdot 10^4$ Pa $\leq S_{tensile} \leq 3.0 \cdot 10^5$ Pa: Fragmentation triggering if $p_{stag} \geq S_{tensile}$
4. D = 4.605 (99 % kinetic energy depletion at the end height)
5. C_D (Kn ≥ 10) = 2.0, C_D (Kn ≤ 0.1) = 0.92
6. μ_{init} = 0.10 (shape change allowed during entry-mean value from ReVelle and Ceplecha, 2001-this conference).

4.2 Varied parameters:

1. Uniform bulk density model (measured values): 1600 kg/m^3 $\leq \rho_m \leq$ 1670 kg/m^3
2. Porous meteoroid model: Volume porosity: $0 \leq \psi \leq 70$ %
3. Initial body radius: $1.0 \leq r \leq 2.5$ m
4. Fundamental atmospheric model parameters: $p_{surf} = 1.01325 \cdot 10^5$ Pa, $\lambda_{surf} = 5.49 \cdot 10^{-8}$ m, g = 9.80665 m/s^2, M_{surf} = 28.966 kg/kmole

4.3 Uniform meteoroid modeling results: μ = 0.10 (Significant shape change)

i) $m_{initial} = 3.70 \cdot 10^4$ kg, $m_{final} = 6.4 \cdot 10^3$ kg (Brown et. al., 2000 estimate 200 kg)
ii) $r_{initial}$ = 1.75 m with predicted ablation= 83 %.
iii) z_{end} = 25.0 km (= 33.95 km with variable σ and break up).
iv) z_{break} = 37-52 km for $6.9 \cdot 10^5 \leq p_S \leq 10^5$ Pa.
v) V_{end} = 9.33 km/s
vi) R_o = 178.6 to 2.2 m, which corresponds to τ_{wave} = 1.62 to 0.02 s (line source blast wave at 10 scaled radii (~1.79 km from the trail).

4.4 Porous meteoroid modeling results: 50 % μ = 0.10 (Significant shape change)

i) $m_{initial} = 6.20 \cdot 10^4$ kg, m_{final} = 1675 kg
ii) $r_{initial}$ = 2 m with predicted ablation= 97 %.
iii) z_{end} = 22.3 km (or 35.7 km with variable σ and break up).
iv) z_{break} = 37-51 km for $6.7 \cdot 10^5 \leq p_S \leq 10^5$ Pa.
v) V_{end} = 8.62 km/s
vi) R_o = 204.2 to 0.43 m, which corresponds to τ_{wave} = 1.85 to 0.0039 s (at 10 scaled radii).

5. GENERALIZED RESULTS: Dynamics and light curves

5.1 Generalized dynamical results

Group I bolides are well explained with bodies of chondritic elemental abundance and nearly zero porosity This is the limit of a uniform chondritic body where the two theories converge in their predictive properties. Groups II, IIIA and IIIB, need progressively larger amounts of porosity to be readily explainable. The degree of porosity necessary must extend from ~ 50 % (group II) to as much as 91 % (group IIIB) to explain their atmospheric dynamical behavior. These results, as summarized in Table 1 at the end of this paper, are given at an entry velocity = 20 km/s, since they are slightly entry velocity dependent.

If the pore spaces are filled with water-ice or other substances, the degree of dynamical agreement rapidly degrades unless the substances themselves are of very low bulk density. For the emission of light we also find agreement with the deduced bolide types with an assumed luminous efficiency factor (constant at all heights). For the progression from $I \rightarrow II \rightarrow IIIA$ for an entry mass of 100 kg at 20 km/s, we find the peak luminosity increasing progressively from -14.3 to -15.1. This porous meteoroid model result stems from the increased surface area for heat transfer processes compared to that for air drag.

5.2 Generalized light emission: Porous meteoroids

We will now generalize the standard light curve expression (Bronshten, 1983) for a homogeneous meteoroid so that we can predict the expected behavior for a porous meteoroid model under similar conditions:

Starting from the relation for a uniform meteoroid:

$$\mathbf{I = -\tau \cdot dE_k /dt}$$

where

$$\mathbf{dE_k /dt \cong (V^2/2)dm/dt = + 0.25\ \rho V^5 \sigma\ C_D\ A}$$

(assuming that $\Delta(z) << 1$ for simplicity)

τ = the differential luminous efficiency for a chondritic meteoroid (uniform in bulk density) and with a specific volume fraction of iron. (This is important since iron dominates many of the lines that have previously been observed spectroscopically for almost all meteors).

We will generalize this expression for a porous meteoroid, first assuming that the luminous efficiency of both types of meteoroids are equal, since their cosmic abundances are nearly the same (iron content, etc.)

Thus, we can write the expression for the light from a porous meteoroid:

$$\mathbf{I^* = -\tau_c \cdot dE_k /dt\,|^*}$$

Now, we can also write that:

$$\mathbf{dE_k /dt\,|^* \ / \ dE_k /dt = (\sigma^* A)/ (\sigma\ A_d)}$$

and using the relation for σ^* found earlier, we can write the above ratio in the form:

$$\mathbf{dE_k /dt\,|^* / dE_k /dt\,|_c = \{A_h/A_d\}^2}$$

Thus, we can now write the ratio of the light output from a porous meteoroid to that for a chondritic uniform density meteoroid in the identical form (since we have assumed that the luminous efficiencies of both types of models have the same numerical value):

$$\mathbf{I^*/I = \{A_h/A_d\}^2 = \{\sigma^* / \sigma\}^2}$$

which is generally much larger than unity if the luminous efficiencies are identical as expected. This clearly explains why the light curves that were determined in ReVelle (1983) continued to become more luminous with all other factors held constant. We explicitly compare this ratio as the final entry in Table 1 at the end of this paper using the uniform and the porous ratios of the values of square of the ablation coefficient. In the limit as the porosity disappears, this expression becomes unity as expected.

This method also gives a physical explanation of why the $(1/I) \cdot dI/dt$ method of Ceplecha et al. (1997) works for the identification of bolide types. Porous (lower density) bodies have inherently larger light curve intensity variations than do nonporous bodies so their $(1/I) \cdot dI/dt$ values should also be inherently greater.

6. SUMMARY AND CONCLUSIONS

We have found very good entry modeling agreement with other approaches (Brown et. al., 2000) that have also determined detailed parameters associated with the fall of the Tagish Lake meteorites (January 18, 2000).

Porous meteoroid modeling is superior to uniform bulk density modeling when simultaneously considering the dynamics, energetics and light curve data of bolides, but especially for this bolide, since it is so porous. For ordinary chondrites, on the other hand, we have the limit of near-zero porosity and the fundamental differences in the two models disappear. Larger ablation coefficients for the porous meteoroid model produces higher end

heights in comparison to uniform bulk density models (ReVelle, 1983). For Tagish Lake this is an end height difference of ~5-10 km.
These larger ablation coefficient produces larger luminosity, at the same mass and velocity, even with the same luminous efficiency factor (ReVelle, 1983). The addition of substances such as water-ice, etc. to the pores degrades the improvement that is gained using a porous meteoroid model.

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Table 1. Comparisons between meteoroid parameters for US PN bolide data using a uniform bulk density model (Ceplecha et. al., 1998) or an inhomogeneous, porous meteoroid model (following ReVelle, 1983).

Type	I.	II.	IIIA.	IIIB.
Uniform model				
ρ_m: g/cm^3	3.7	2.0	0.75	0.27
σ: s^2/km^2	0.014	0.042	0.10	0.21
Porous model	ψ'= 0%	ψ'= 50%	ψ'= 75%	ψ'= 91%
ρ_m: g/cm^3	3.7	1.85	0.93	0.34
σ: s^2/km^2	0.02	0.04	0.08	0.22
I^*/I: Uniform σ values	1.0	9.0	51.0	225.0
I^*/I: Porous σ values	1.0	4.0	16.0	121.0

Table 2. Preliminary Tagish Lake results

Model type: μ = 2/3: Constant σ solutions	Uniform: $m_{initial}$ = $3.70 \cdot 10^4$ kg, $r_{initial}$ = 1.75 m	Porous : 60 % $m_{initial}$ = $4.96 \cdot 10^4$ kg, $r_{initial}$ = 2.00 m
Starting height	67.50	67.33
V at max. light	12.05	12.34
Height of max. light: km	32.76	33.24
Height where $p_{stag} > T_s$: km	35-51 for p_s: 10^5 to $8 \cdot 10^5$ Pa	34-52 for p_s: 10^5 to $6 \cdot 10^5$ Pa
Height of max. m· dV/dt: km	29.43	30.49
End height velocity: km/s	9.33	9.93
End height: km	19.3 (31.1 for variable σ with break up)	20.0 (33.9 for variable σ with break up)
Predicted Ablation	82 %	98 %
Terminal mass	m_{final} = 6,794kg	m_{final} = 979.4kg