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Title:

THEORETICAL LEONID ENTRY MODELING

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ABSTRACT

In this work we present a model originally developed by ReVelle (1979, 1993) that has been applied to model large Leonid bolides with a few relatively minor modifications and one major modification which allows for catastrophic "pancake: fragmentation processes as described below. The minor modifications include allowing the energy of ablation per unit mass for vaporization, Q_{vap}, to be a free variable that is adjusted until agreement is obtained between the theoretical model and the statistically expected ablation coefficient for the Leonids (Group IIIB type bolide). It was found that the Q_{vap} had to be reduced by a factor of about five times compared to the accepted value of Q_{vap} for cometary materials. Alternative ways of achieving this degree of agreement between theory and observations are also suggested as well. In a separate paper we apply this model to a specific Leonid bolide during the 1998 storm period.

1. INTRODUCTION AND OVERVIEW

1.1 <u>Key assumptions</u>- following Levin (1961), Bronshten (1993) and ReVelle (1999):

We start from the numerical solution proposed by ReVelle (1979, 1993, 2000) which comes from an analytic solution for hypersonic meteoroid entry, assuming a hydrostatic, isothermal, atmosphere with the ablation coefficient, σ, a constant and a height variable velocity. This solution simultaneously includes ablation, deceleration, shape change and fragmentation while neglecting lift, coriolis effects and gravity gradients, etc.

1.2 <u>Fundamental regimes:</u>

i) $|H_p / H_f| \ll 1$: Single-body model

where

H_f = Fragmentation scale height
H_p = Pressure scale height

This limit includes a self-similar ablation solution with no shape change for $\mu \equiv 2/3$.
For $0 \le \mu < 2/3$, the solution includes ablation and deceleration, as well as shape change with the frontal cross-sectional area, A(z), decreasing with decreasing height

ii) $H_p / H_f \gg 1$:
Catastrophic fragmentation limit

With $\mu < 0$, this solution allows for ablation and deceleration as well as shape change, but A(z) increases with decreasing height.

2. ENTRY MODELING APPROACH: OVERALL SUMMARY

2.1 <u>Key assumptions</u>

An entry modeling summary can be found in ReVelle (1979, 1985, 1993, 1999). In order to model the very high speed Leonids, we will regard all variables as known as in ReVelle (1979), except for the energy of ablation/mass, Q_i, for the Leonid's as a function of $k = V_\infty^2 / (2 \cdot Q_{vap})$, the ablation interaction number. For $Q_{vap} \cong 3.8$ MJ/kg, $V_\infty = 70.7$ km/s, $k \cong 657.7$. From previous arcjet wind tunnel data for chondritic meteorites, vaporization occurs at the stagnation point if k > ~25 so there seems to be little doubt that the Leonid's will vaporize profusely.
For large bodies (radius > ~ 1 cm), we will neglect the gas cap absorption of the radiative energy emission from the high temperature leading shock wave. If this effect had been included, this may allow substantial agreement to be obtained between modeling and observations, without systematically decreasing Q_{vap}. We will also neglect precursor ionization

(which is also called free stream absorption by hypersonic aerodynamicists) ahead of the body, i.e., we will assume no preheating of the local air by the strong ultraviolet radiation from the shock wave. At the end height of the interaction for a typical Leonid bolide, the neutral air density is quite low while the mean free path is somewhat less than the body radius so that the near-continuum flow regime has been reached. Thus this preheating is unlikely to be very significant for the Leonids. We will also assume that single-body theory ($|H_f| >> H_p$) with a height variable ablation coefficient and velocity, etc. is adequate until the stagnation pressure exceeds the tensile/compressive strength of an "average" Leonid. If this occurs, we computed the fragmentation scale height (ReVelle, 2001) as a function of the μ parameter (Bronshten , 1983) to evaluate the entry behavior at still lower altitudes.

2.2 <u>Single-body approximation approach:</u>

In this work we have adopted the formal approach developed in ReVelle (1979, 1993, 1999) where the generalized form of the analytic solution of the equations for the dynamics and energetics of large meteor entry for the limiting case of constant coefficients was solved numerically. Within each small numerical time (or altitude) interval, the relevant coefficients at each height were assumed constant and explicitly calculated using analytic expressions that had been derived for each of the relevant heat transfer terms. In this paper we have also added the effects of shape change on the solution as well using the μ parameter. Next, starting at sufficiently high altitude, we have computed the Knudsen number, Kn, (local neutral gas mean free path divided by the body radius) over a sufficiently small height interval such that the computed ablation coefficient was slowly varying over all heights:

$$(1/\sigma_o)\cdot\partial\sigma/\partial z\cdot\delta z << 1$$

This limiting condition formally results from an explicit power series expansion of σ which can be expressed to first order in the form:

$$\sigma(z) = \sigma_o+\{\partial\sigma/\partial z\}\cdot\delta z+ \ldots \text{ (higher order terms)}$$

LTE (local thermodynamic equilibrium) was assumed throughout all of these calculations. The calculations were further also evaluated within each height interval according to the magnitude of the Knudsen number since this completely controls the relevant aerodynamical possibilities for hypersonic flows:

i) **If Kn > 10:**
Free molecule flow relations from laboratory experiments were utilized

ii) **If 10 > Kn > 0.1:**

Analytic flow bridging expressions between the limiting regimes were utilized (based on kinetic theory expansions in Kn)

iii) **If Kn < 0.1:**

Continuum flow regime

In the latter case, we computed gas cap (boundary layer) state and decided if it was either turbulent or laminar. We then computed either the laminar or turbulent convective heat transfer and the corresponding radiative heat transfer coefficients. These coefficients were normalized and summed in order to get the total equilibrium heat transfer coefficient. During all of these calculations, we computed the variable ablation coefficient as height changes (over small altitude intervals). We also computed the percentage ablation and the corresponding instantaneous mass, size, shape factor, stagnation pressure and velocity as well as the next value of Kn in order to evaluate the flow regime during the next height step, etc. In addition, we computed the relevant line source blast wave relaxation radius and relevant infrasound properties since these large bodies can generate infrasonic signals that can be detected at the ground (ReVelle, 1976, ReVelle, 1997, ReVelle and Whitaker, 1999)

3. APPLICATION TO LARGE LEONID BOLIDES

3.1 <u>Leonid material properties:</u>

In order to complete the entry model for application to the Leonids, we first require their material properties. We expect that the large Leonids to be of type IIIB meteor-fireballs (weak cometary materials). The statistically expected bulk density is 270 kg/m^3. If these are porous, chondritic bodies, their degree of porosity is ~91 % (ReVelle, 1983, 2001). The expected ablation coefficient is 0.21 kg/MJ (1 MJ = 10^6 J) and their energy of ablation/mass is 3.8 MJ/kg (Jessberger et. al., 1988). We initially assumed a spherical shape with a corresponding shape factor: 1.208. Next we consider the shape change parameter, μ , and its implications for the possible solutions. In general as μ decreases the corresponding bolide end height increases. If for example, $\mu = 2/3$, a self-similar solution with no shape change is predicted. Until recently (although see ReVelle, 1980) this was the standard solution type assumed since there are so many free variables in the entry problem even without considering the luminosity part of the prediction problem. For $0 \le \mu < 2/3$, solutions with shape change and simultaneous ablation and deceleration are allowed. For $\mu < 0$, a catastrophic break-up, subject to a stagnation pressure onset criterion is predicted (for details see ReVelle, 2001). In addition we also need values of the drag coefficients. These values are of the drag coefficient for free-molecular hypersonic flow, $C_{Do} = 2.00$ and for continuum hypersonic flow (for a sphere), $C_{Doo} = 0.92$. Values of the dimensionless heat transfer coefficient, C_h , were taken from arcjet wind tunnel experiments in the free molecule flow regime as quoted in ReVelle (1979).

3.2 Bolide dynamics and energetics :

Following ReVelle (1993) we have used an energetics approach that follows from the standard dynamical equations given in Ceplecha (1998). This approach relies on the D parameter (from $E_k = E_{k\infty} \cdot \exp[-D]$) which specifies the kinetic energy that will remain at the end height. For example, for D = 2.303, 10 % of the initial kinetic energy has been removed at the end height whereas for D = 4.603, 99 % of the initial kinetic energy has been removed (or 1 % remaining). We expect on the basis of the observed end height velocities that the smaller D values correspond to weaker bodies of cometary origin (smaller decelerations) and vice versa.

In this approach, we first solve iteratively for the end height velocity, V_{end} (when $V(z) = V_{end}$):

$$\mathbf{V(z) = V_\infty \cdot exp[(\sigma/4) \cdot \{V_\infty^2 - V^2(z)\}] \cdot exp[-D/2]}$$

This equation predicts the end height velocity as a function of D and σ.

The resulting end height equation for a constant ablation coefficient is given by:

$$\mathbf{z_{KE}(V) = -H_p \cdot \{ln(p_\infty^*/p_o) \cdot exp[-(\sigma \cdot A) \cdot V_\infty^2] \cdot \{D - D'\} + exp[-z'/H_p]\}}$$

$$\mathbf{z' = -H_p \cdot \{ln(p_\infty^*/p_o) \cdot (2gH_p/V_\infty^2)\}}$$

where

z' is the altitude where dV/dt = 0 initially

$$\mathbf{D' = -\{Ei[(\sigma \cdot A) \cdot V_\infty^2] - Ei[(\sigma \cdot A) \cdot V^2(z)] - ln(V_\infty/V(z))^2 - [(\sigma/2)(V_\infty^2 - V^2(z))]\}}$$

$Ei(\sigma \cdot A)$ = the exponential integral function
$A = (1-\mu)/2$
p_o = surface pressure
$p_\infty^* = mg \cdot \sin\theta/(C_D A)$
" = Modified ballistic entry parameter
$p_\infty^* = 4 \cdot \rho_m \cdot r \cdot g \cdot \sin\theta/(3C_D)$ for a sphere

3.3 Ablation model assumptions:

We have assumed that when the instantaneous bolide velocity ≤ 3 km/s, all ablation will cease (before the aerodynamic cold wall approximation breaks down since the shock temperature lowers significantly as the bolide velocity decreases). This assumption is in agreement with wind tunnel experiments with meteorite samples. Also, when the entry velocity is sufficiently small (large), stagnation point ablation proceeds directly by melting (vaporization). This is numerically evaluated by calculating the ablation interaction number, k, as mentioned earlier. The specific velocity limits between melting and vaporization were chosen purely empirically based on arc-jet wind tunnel ablative observations (from NASA-Langley's former PERF-Planetary Entry Radiation Facility). Finally, when the entry velocity is intermediate in its magnitude, a mix of ablative processes is assumed to occur near the stagnation point whose energy of ablation/mass is also intermediate to that of either pure melting or pure vaporization.

3.4 More calculation details

The laminar heat transfer through this plasma can be decomposed into at least three identifiable parts, of which the first two are the most significant:

i) Heat transfer by conduction through the plasma
ii) Heat transfer due to mass diffusion caused by concentration gradients
iii) Heat transfer due to mass diffusion caused by thermal gradients.

There are also additional heat transfer mechanisms including those in transitional and in free molecular flow. For example, we expect a shielded impact of the oncoming flow with the meteoroid ($Kn > \sim O(1)$).There is also a turbulent plasma conductive/convective heat transfer depending on the flow conditions and on the Stanton number as well as a radiative heat transfer during continuum flow (ReVelle, 1979). There are also non-equilibrium turbulent and radiative heat transfer coefficients that have not been included in this analysis, since such effects are generally only important at sufficiently high altitudes where the ablation itself is also very small regardless of the magnitude of the ablation coefficient. Since we have not discussed the equilibrium radiative heat transfer in great detail before we will focus on that subject directly below.

3.5 Radiation transfer predictions:

Here we can divide the problem up into unshielded versus shielded (radiation blockage) flows. The key dimensionless parameters for a one-dimensional model are the Re (Reynolds number), Bu (Bouger number), Bo (Goulard number). Alternatively, we can also use: Γ (Radiation-convection parameter) instead of Bo. The specific gas opacity limits are respectively an optically thin gas cap specified by $Bu \ll 1$ and an optically thick gas cap specified by $Bu \gg 1$. The radiation transfer calculations have been carried out assuming that the flow is axisymmetric flow over a blunt body at its stagnation point. The shock wave radiation flux and turbulent heat flux are assumed to be uncoupled and thus can be calculated separately. This is in agreement with the well known and reliable reference enthalpy approach. This approximation is most reliable however for $Bu \gg 1$. The front face of the bolide has been assumed to be a cold, non-reflecting black wall (assumed: “cold” with respect to the plasma gas cap and the leading shock front). The air in the high temperature plasma of the gas cap is assumed to be >10,000 K: Also, both local thermodynamic equilibrium (LTE) and chemical equilibrium have been assumed in the inviscid, non-heat conducting plasma. As mentioned above non-equilibrium processes have not been incorporated. The solution available to solve the equations of *Radiation Gas Dynamics* called the Method of Integral Relations, which is acceptable for all subsonic flow regions with respect to the body. These equations are a system of integro-differential equations with flow-coupled radiative transfer and simultaneous solution of the mass, momentum and energy conservation equations. The 1-D (one-dimensional) radiation transfer model (RATRAP) utilizes the tangent slab approximation and is due originally to Wilson (1972). Both atomic line radiation and continuum radiation in a non-gray gas are included in the numerical computations as well as self absorption in the plasma.

ReVelle (1976, 1979) predicted a limiting value of the radiative heating coefficient at speeds > 20 km/s because of the presence of strong radiative cooling by the initially very high temperature of the gas cap plasma. This limiting behavior is directly observable in the numerical simulations at progressively larger velocities. Ablation products absorption in the gas cap plasma has not been not incorporated (unshielded flows) as will be discussed later. Also as mentioned earlier precursor ionization (free stream absorption) ahead of the body is not calculated. This also applies to wavelength-dependent radiative coupling in the gas cap's turbulent boundary layer, which also has not been considered. The equations used for this calculation are given in ReVelle (1979).

The radiation transfer for shielded flows (blockage) by ablated vapors has been calculated by a number of different authors. In some cases the radiative heating coefficient was reduced by up to ~90%, but in other cases, it was much smaller. Unfortunately if this blockage effect is significant for the Leonids, we are faced with reducing Q_{vap} even further than has already been suggested in this paper compared to the currently quoted values in the literature.

Although this topic is extremely complicated , one obvious question is whether this energy is simply convected into the wake or whether is it reradiated in different spectral regions downstream of the stagnation point? Part of the answer to these questions depends on the composition of the inhomogeneous body. Some of the numerous elements that have been identified in the spectra of bolides are included in the following list: Fe, Ni, Na, Li, C, Ca, Cr, Mn, Mg, Al, Si, K, Co, etc. The degree to which this absorption of the radiative emission from the leading shock front is also dependent upon the ablated vapor properties in a very high temperature, low density plasma (with very large gradients). ReVelle (2000) addressed this issue using scaling arguments for translational motion and decided that it should not be very important for the Leonids because of their very high entry velocity, but for slower bolides it could play a more significant role. Furthermore this also depends on position of the flow relative to the stagnation point: In two-dimensional (2-D) flows, a nearly Gaussian heating profile prevails (ReVelle, 1980), but it also depends on the rotation rate and on the axis of the rotational relative to the flow. Clearly there will be less reduction of the radiative emission by ablative vapors near the body if ablation occurs with a mixture of melting and vaporization and none at all if only melting is occurring.

In this work we have not modeled either the normalized or un-normalized light from bolides, but it will be a topic of a forthcoming publication. It is also briefly discussed in ReVelle (2001a). Line source blast wave interactions and shock wave development and subsequent propagation of infrasound are also not considered here, but are covered in other references of the author ReVelle (1997, 2001b)

4. SUMMARY AND CONCLUSIONS

The Leonids experience probably the most severe atmospheric entry conditions. We have tested sizes from 10^{-3} to 10 m. Extensive ablation is predicted, generally exceeding ~ 90 %. Using a Q_i value for vaporization which is approximately five times smaller than the proposed value for cometary materials, we obtained a height averaged ablation coefficient of ~ 0.20 kg/MJ in agreement with Ceplecha et al. (1998). The fundamental flow regime conditions can cover the entire range from free molecular to continuum flow over the mass range from $1.31 \cdot 10^{-6}$-$1.31 \cdot 10^{6}$ kg.

The ablation coefficient can be nearly constant or be distinctly height variable, depending on the initial body size. The shock wave radiation is a dominant heat transfer contributor for the larger bodies tested with plasma convective (or laminar conductive) heat transfer dominated for the smaller bodies At certain altitudes turbulent for the largest bodies above about 1 m in radius, convective heat transfer can also be very important. Can this laminar/turbulent boundary layer transition affect the predicted and observed light curve? Preliminary results soon to be published suggest that it effect is significant for a certain size range of bodies. In addition, for large Leonids, strong shock, blast wave generation and consequently infrasound propagation with subsequent ground-based detection is readily possible. This was recently demonstrated for the Leonids by ReVelle and Whitaker (1999).

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