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CALCULATIONS OF SHAPE CHANGE AND FRAGMENTATION PARAMETERS USING VERY PRECISE BOLIDE DATA

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ABSTRACT

Using the theoretical formalism of ReVelle (2001d), we have analyzed 22 European (EN) and US Prairie Network fireballs (PN) with the most precise trajectory information available for shape change and fragmentation effects. For 14 bolides the shape change parameter, μ, was always > 0 and for the other 8 cases there were instances of μ < 0, but with large oscillations in its sign with height or time. When the shape change parameter, μ, was < 0, the fragmentation scale height was > 0 and in a few instances was briefly even smaller than the pressure scale height. This is the necessary condition in addition to the sufficient condition of μ < 0 for the onset of the catastrophic fragmentation process ("pancake" break-up). A histogram of all computed μ values indicates that an average value was <μ > ≅ 0.10, indicating that substantial shape change has taken place during entry for these bolides. This is fully consistent with the recent analyses of ReVelle and Ceplecha (2001g) of the changes in the shape-density coefficient, K, with time as well. Thus, the use of the μ = 2/3 (self-similar solution with no shape change) is not recommended for bolide modeling efforts. From our results we can conclude that most of the US DoD bolides can be successfully modeled using single-body theory without resorting to the "pancake" catastrophic fragmentation model that was "rediscovered" in the early 1990's by a number of workers. These researchers included Hills and Goda, Chyba, Thomas and Zahnle, etc. who specifically developed this break-up model for studying he impact into Jupiter of the huge Shoemaker Levy-9 comet.

1. INTRODUCTION AND OVERVIEW:

1.1 Previous modern fragmentation modeling

Various break-up schemes have been devised in order to correct the conventional single-body model for the effects of fragmentation processes. These include modifications of the drag and heat transfer areas in a systematic manner as described in ReVelle (2001d) for both homogeneous and porous meteoroids.

Several possible break-up mechanisms have been previously proposed including thermal break-up due to heating effects, but this is very inefficient, especially for the typical chondritic materials with very low thermal conductivity. On the other hand, mechanical break-up effects due to pressure loading which are triggered by stagnation pressure exceeding the uni-axial tensile or compressive strength of the body seem very plausible. The observed premature, early break-up at very low stagnation pressures are presumably due to additional weaknesses fin the body from cracks due to prior space collisions.

1.2 Analyses of bolide behavior in the atmosphere

In our analysis we have used what are now standard bolide analysis techniques (Ceplecha et. al., 1998) for determining the altitude behavior of various meteoroid flight parameters, including the velocity, V and its derivatives, the ablation parameter, σ, the shape-density coefficient, K and the shape change parameter, μ, etc. The reference model atmosphere used is the monthly mean value as a function of height and month for the CIRA 1977 standard atmosphere. These fireballs have also previously been analyzed for their possible gross-fragmentation behavior as well.

2. MODELING OF BOLIDE FRAGMENTATION PROCESSES: LIMITING BEHAVIOR

In this paper we will only analyze the fragmentation possibilities in two distinct limits, namely:

i) Single-body model limit
ii) Catastrophic "pancake" type fragmentation limit

The definitions of these regimes are as follows:

2.1 Single-body model limit:

Criterion: $|H_f| \gg H_p$

where

H_f = Fragmentation scale height

$\mathbf{H_f = -f(z)/\partial f/\partial z \; ; \; f \equiv A(z)/A_\infty}$,

H_p = Pressure scale height

$\mathbf{H_p = -p(z)/\partial p/\partial z = RT/g}$ (if the atmosphere is in exact hydrostatic balance)
$H_p \sim$ 6-8 km from $0 \le z \le 120$ km for the "real" atmosphere

2.2 Catastrophic "pancake" fragmentation:

Criterion: $H_f \ll H_p$

Physically, H_f is the downward vertical distance scale by which the bolide frontal cross-sectional area increases by 1/e. This parameter can be determined directly from the approach originally due to Levin and developed in Bronshten (1983). This is readily evident from the definition of the μ parameter when it is < 0. The definition of μ is**:**

$$\mu = d(\ln(K)/d(\ln(m)) \cong \Delta(\ln(K)/\Delta(\ln(m))$$

where

K = Shape-density coefficient
m = instantaneous dynamic mass

If stagnation pressure loading on the frontal cross-section is the fundamental mechanism for break-up, Otherwise, for $\mu > 0$, only quasi-continuous fragmentation processes can occur under these assumptions.

We have not yet evaluated the effects of < 0 on the light emitted during the bolide-atmosphere interaction process. Such details will appear in a forthcoming paper.

3. ANALYSIS OF 22 VERY PRECISE PN AND EN BOLIDES (assuming a uniform bulk density model)

Following ReVelle and Ceplecha (2001g), we have analyzed 22 of the best-observed PN and EN bolides with very precise trajectory data in order to evaluate the fragmentation possibilities. A list of the bolides analyzed are as follows (PN designates US Prairie network fireballs and O designates Ondrejov observatory fireballs which is a part of the European fireball network (EN):

i) PN38737, PN38768
ii) PN38827 (∗), PN39122
iii) PN39154, PN39197 (∗)
iv) PN39424B, PN39476
v) PN39499, PN39509C (∗)
vi) PN39608, PN39820B (∗)
vii) PN39828, PN39938B (∗)
viii) PN40379A, PN41280,
ix) PN41432, PN41593 (∗),
x) PN41827
xi) O24421, O27471 (∗)
xii) O32202 (∗)

(∗) Bolides with very significant negative μ and positive H_f.

3.1 Cases with μ > 0

From our analyses of these data, we have found that 14 bolides have μ entirely positive. Also, there are no systematic μ values > 0 as a function of height smaller than 0.10. The equation used to evaluate the fragmentation scale height, H_f evaluated from individual values of $\mu(z)$, $\sigma(z)$ and of $V(z)$ and of $dV(z)/dt$:

$$\mathbf{H_f(z) = \sin\theta/\{\mu(z)\cdot\sigma(z)\cdot dV(z)/dt\}}$$

where

$\sin\theta = \cos(Z_R)$
Z_R = Zenith angle of the radiant

In our analysis θ was assumed to be constant which is an excellent approximation over most of the trajectory. The following variables were explicitly determined along the trajectory:

i) V(z) and dV(z)/dt
ii) σ (z)

The μ parameter was computed from a finite difference height derivative indicated earlier generally over a few km height interval along the trajectory (smaller height differences were attempted, but they did yield reliable results). We can readily conclude from our work that μ is definitely not a constant with either height or time as assumed in the original theory of Levin.

A histogram of μ versus the total number of bolides in our sample indicates that the < μ > ≅ 0.10 (see Table 1. below). Since the classical value for self-similar behavior with no shape change is 2/3, (Bronshten, 1983) we are left with the very reasonable conclusion that most bolides also experience significant shape change due to ablation during their entry into the atmosphere.

Table 1: Histogram of Results

μ	**Number of cases (*)**
< -2.0	**4**
-1.0 to -2.0	**2**
-0.67 to -1.0	**2**
-0.33 to -0.67	**1**
0 to -0.33	**7**
0 to 0.33	**23**
0.33 to 0.67	**10**
0.67 to 1.0	**7**
1.0 to 2.0	**6**
> 2.0	**9**

(*) 71 values of μ with standard deviations exceeding the value by > 3 times for 22 bolides

Thus, the mean value for all cases is about 0.10. This indicates that a large amount of shape change is taking place during entry for these bolides.

In Table 2. below we have indicated a representative summary of the altitude profile of the cases for μ > 0. In this table we have also indicated each of the starting and ending height intervals (h_1 and h_2) for the evaluations of μ as well as the individual μ values and their computed standard deviations inside each of these intervals. Although there is one case with μ slightly > 0, if we consider the computed formal standard deviation of μ, this value is clearly not significant.

3.2 Cases with μ < 0

From our analyses of these data, we have found that 8 cases with μ < 0, i.e., with "pancake" type catastrophic fragmentation. In our analysis, we have found that if μ is negative, the position(s) where this occurs along the trajectory can generally occur either quite early during entry or quite close to the terminal point.

The latter behavior is consistent with the concept that fragmentation being triggered by stagnation pressure loading, but what is happening very early during entry is still quite puzzling. Also, μ is clearly not constant along the trajectory in regions where it is negative. Although systematic values of μ that have been identified can exceed -10 (PN41593), most calculated negative μ values are much smaller. Very rarely are |μ| values larger than 2 to 4 and most < |μ|> are < 0.35. Also, we have found that μ values can alternate between positive and negative for an individual bolide case. We have also found that there is no clearly observed dependence of μ on mass, deceleration, velocity or altitude.

Regarding the fragmentation scale height, H_f, it was found to be positive in regions where μ < 0 and varies between the limits of very small values (somewhat less than the pressure scale height, H_p) to very large values. For conditions near the terminal point, H_f is slightly < H_p for the following bolides:

i) O32202, PN39509C, PN39820B, PN39938B

and earlier in the trajectory for:

ii) O27471, PN39938B

In Table 3. below we have indicated a representative summary of the altitude profile of the cases for μ < 0. Three of these five cases have μ < 0 near to the start of the visible trajectory which is not readily understandable unless break-up is occurring due to weaknesses in the bodies (from pre-existing cracks) which lower the effective strength at which stagnation pressure loading can trigger fragmentation. There is one such case presented with a very large negative μ (PN41593). Even allowing for deviations as large as three standard deviations about the mean, this μ value is clearly < 0 and very significant. Obviously such cases require much more detailed study. Finally, we have the PN39938B case for which $\mu < 0$ at two different heights along the trajectory, both of which are statistically significant at the three standard deviation level.

4. SUMMARY AND CONCLUSIONS

Using a newly discovered concept, the Fragmentation scale height, $H_f(z)$ and the μ parameter originally devised by Levin, we have systematically analyzed the flight trajectory data of 22 of the most precise US Prairie Network and European network bolides. For these cases we have found that 14 cases satisfy the standard single-body model that follows the criterion:

$$\textbf{i)}\ H_f(z) \gg H_p(z)$$

We have also found that 8 cases which have $\mu < 0$ in some altitude interval such that catastrophic "pancake" break-up behavior is possible over some small height interval if:

$$\textbf{ii)}\ H_f(z) \ll H_p(z)$$

Assuming that μ is ≠ f(body size) and not too negative ($|\mu| < 3.33$), ReVelle (2001d) has concluded that for μ= constant, the start of "pancake" fragmentation occurs for lower density bolides of higher initial speed, at shallower entry angles and having a relatively large ablation coefficient. From the analysis of ReVelle (2001d), we can conclude that larger (smaller) bodies can only break-up if they are exceptionally strong (weak). Still larger negative μ values require increases in the frontal cross-section of the body that are not defensible in this authors' opinion unless the process of the tearing of the body laterally is intrinsically unstable. This in fact seems to be demonstrated both by the observed extreme variations of μ with height and with its rapid change in sign across relatively small altitude intervals.

From the work of ReVelle (2001d), there appears to be an optimum range of masses for which this type of fragmentation can occur (if μ = constant). Recall however that all of the catastrophic fragmentation "pancake" models were originally developed for the study of very very large bodies (hundreds of meters to kilometers across). This is a puzzle however given the work of ReVelle (2001d) and its conclusions regarding the relative sizes needed for this process to be viable (again for μ = constant) . The range of applicability of the original pancake models is thought to be extremely limited for the small bodies of the size typically observed by ground-based camera networks (J. G. Hills, personal communication, 2001). Clearly this difference of the relevant body size for this process needs to be more fully understood. We still conclude that many bolides (including the frequently observed US DoD bolides) can be safely treated using the single-body theory with $\mu > 0$. "Pancake" type break-up is generally not expected.

Direct observations of 22 of the most precise bolides does not show much support for a catastrophic type break-up for bodies up to ~ 1 m across. Only 8 of 22 bolides exhibited any significantly negative μ values.

5. REFERENCES:

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Table 2. Representative summary of individual bolide data: With $\mu > 0$.

Number	h_1	h_1	μ	Std. dev. of μ
O24421	72.7	62.5	1.0	±0.40
O24421	62.5	59.0	-0.06	±0.03
O24421	59.0	55.3	0.32	±0.03
O24421	55.3	50.7	0.42	±0.08
PN39154	67.0	58.0	4.0	±1.4
PN39154	58.0	46.6	1.1	±0.30
PN39154	46.6	41.2	0.0	±0.10
PN39499	65.7	41.0	0.76	±0.07
PN39499	41.0	38.6	0.19	±0.04
PN39499	38.6	37.0	0.37	±0.02
PN39608	67.4	57.8	2.0	±0.20
PN39608	57.8	54.3	0.0	±0.04
PN39608	54.3	50.3	0.34	±0.03
PN39608	50.3	48.3	1.0	±0.20

Table 3. Representative summary of individual bolide data: With $\mu < 0$.

Number	h_1	h_1	μ	Std. dev. of μ
O27471	60.7	56.9	-3.9	±0.30
O27471	56.9	54.1	2.0	±0.70
O27471	54.1	52.1	-1.4	±0.20
O27471	52.1	41.6	-0.02	±0.01
O32202	76.4	68.0	-0.03	±0.02
O32202	68.0	66.0	1.1	±0.10
O32202	66.0	64.9	-0.80	±0.20
PN38827	78.3	56.8	4.8	±0.50
PN38827	56.8	52.0	-0.68	±0.23
PN38827	52.0	48.0	0.11	±0.05
PN38827	48.0	45.3	0.71	±0.20
PN39938	60.6	55.2	8.1	±0.70 (*)
PN39938	55.2	50.0	0.7	±0.70
PN39938	50.0	43.9	-0.38	±0.09
PN39938	43.9	42.3	2.7	±0.30
PN39938	42.3	40.6	-3.1	±0.70
PN41593	62.8	58.3	-12.0	±2.0
PN41593	58.3	34.9	0.36	±0.01
PN41593	34.9	33.3	0.05	±0.01

(*) All entries for this case are for PN39938B.