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FRAGMENTATION OF WEAK NON-ABLATING OBJECTS DURING ENTRY

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FRAGMENTATION OF WEAK NON-ABLATING OBJECTS DURING ENTRY

Gregory H. Canavan

Fragmentation of objects during entry can be treated with developed models of breakup, fragment cascade, separation, and deceleration. The results reduce to those derived earlier for strong objects. Model predictions are in agreement with the key features of numerical simulations. Model equations can be inverted analytically to infer object size, entry speed, and strength from measurements of peak power and altitude and fragmentation altitude or time.

Introduction. This note discusses the breakup of non-ablating and ablating objects during entry. It uses kinematic results from previous reports to describe the velocity and pressure of entering objects. It adds treatments of the breakup of objects during deceleration and of the breakup and separation of fragments during their further descent. It estimates the mass per area as a function of altitude and uses it to determine the altitude and magnitude of peak power radiation. These results reduce to those derived earlier for strong objects in that limit. Model predictions are shown to be in agreement with the key features of numerical calculations of fracture during deceleration. It is shown that the model equations can be readily inverted analytically to infer object size, entry speed, and strength from measurements of peak power and altitude and fragmentation altitude or time.

Analysis of breakup. Deceleration during entry produces ram pressure p on the front surface of the object. If p exceeds the object's strength S , the object will fracture and break up. The pressure on the front surface is

$$p = C\rho V^2, \quad (1)$$

where C (≈ 2) is its drag coefficient, ρ is the local density, and V is its instantaneous velocity. Earlier reports have shown that to adequate accuracy, the velocity can be approximated by

$$V = V_0 e^{-\rho H/\beta}, \quad (2)$$

where V_0 is its initial speed and $\beta = 0.7\rho_a D$ is its mass per unit area or ballistic coefficient. Thus, the pressure is

$$p = C\rho V_0^2 e^{-2\rho H/\beta}, \quad (3)$$

Fig. 1 } which is shown as a function of altitude z for various values of D for $V_0 = 20$ km/s. The nominal 1,000, 100, 10, and 1 bar (atmosphere) yield stresses for iron, stone, carbon, and comet materials are also shown for reference. For larger objects, the peak pressure is larger and at lower altitudes because the object does not decelerate until $\rho \approx \beta/H \propto D$. For 20 km/s, the pressure reaches about 1,000 bars for a 1 m object and 3,500 bars for a 4 m object. The pressure scales as V_0^2 , so at 10 km/s, the 4 m object would only reach about 900 bars.

For 20 km/s, the strength of 2 and 4 m iron objects is exceeded at 13-15 km. That of all stone objects is exceeded at about 30 km. The strength of carbon and cometary materials is exceeded at above 40 km, which is why comets break up high. For the large objects, the pressure increases exponentially with ρ , so the points of intersection are insensitive to the precise value of S . The smaller objects are slowed by drag, so their increase is more gradual, and the value of S used is significant. The pressure curves are shown as remaining above the corresponding S for some tens of kilometers, but these drag curves ignore the increase in β due to breakup, which slows the objects much more rapidly, as discussed below. The altitude of peak pressure can be determined by differentiating Eq. (3) as $\rho_m = \beta/2H$, where

$$p_m = CV_0^2 \beta / 2eH, \quad (4)$$

which is shown in Fig. 2 as a function of D for various values of V_0 . If the peak pressure is less than S , the object does not break, and its entry may be treated with the solution for a strong, hard object presented earlier.¹ Iron asteroids with diameters of 4, 2, 1, and 0.5 m would breakup at speeds of about 10, 15, 20, and 25 km/s, respectively. At 5 km/s only stone objects larger than 2 m would penetrate deeply enough to breakup. Thus, fragmentation is a phenomena reserved for relatively large and fast non-ablating objects.

If the object fragments, it does so at the higher altitude intercept, z_f , on the rising side of density, so that $S \propto C_p V_0^2$, or

$$\rho \approx S / CV_0^2, \quad (5)$$

$$Z_f \approx -H \ln (S / CV_0^2),$$

where H is the atmospheric scale height. Figure 3 shows Z_f vs S for V_0 from 5 to 25 km/s for large D . For 20-25 km/s, fragmentation occurs at about 20 km even for strong objects. The ≈ 14 km/s corresponds closely with the fragmentation altitude of the 4 m object on Fig. 1. As the speed decreases, the objects penetrate to much lower altitudes before fragmentation. At 5 km/s large objects would make it all the way to the ground.

As the fragmentation altitudes are well above the altitude that gives maximum pressure in Eq. (4) and Fig. 2, they are relatively insensitive to the objects β . Object size does enter in one important way, however. For $p_m > S$ to hold requires that $D > 2eHS/1.3C_p aDV_0^2$, which gives about 1 m for a 10 km/s stone object. This limit holds for any S for large D .

Subsequent fragmentation. If the pressure exceeds the objects strength, the object fragments. If the fragments remain relatively close together, that increases their total effective area, which causes the fragments to decelerate faster. If the pressure on a fragment remains larger than its strength, it will fragment as well. That process can proceed through a number of generations until the fragments move apart or are decelerated enough to reduce the pressure on them below their strength, at which altitude the process stops. Below that altitude the fragments descend as individual small objects. This process can be modeled approximately. After breakup

at altitude Z_f from Eq. (5), as the fragments continue downward, they drift apart at a transverse speed that is estimated to be on the order of²

$$V_t \approx k\sqrt{(\rho_f/\rho_a)} V, \quad (6)$$

where ρ_f is the density at the breakup altitude and $k \approx 1$ is a constant. As $\rho_a \approx 3,000 \text{ kg/m}^3$ and $\rho_f \approx 0.01 \text{ kg/m}^3$ at typical breakup altitudes, $\sqrt{(\rho_f/\rho_a)} \approx 0.002$, so $V_t \approx 0.002 V \approx 40 \text{ km/s}$, which is significant. In descending a distance h , the collection of fragments expands to diameter

$$D_f \approx V_t h/V \approx k\sqrt{(\rho_f/\rho_a)} h, \quad (7)$$

and area

$$D_f^2 \approx k^2(\rho_f/\rho_a) h^2. \quad (8)$$

Previous reports have shown that deceleration occurs very rapidly at the density equal to the object's ballistic coefficient divided by the scale height, or³

$$\rho_d \approx \beta_d/H, \quad (9)$$

where β_d is the ballistic coefficient, M/D_f^2 , based on the increased area of Eq. (8), where $M \approx \rho_a D^3/2$, and the densities at heights separated by h are related by

$$\rho_f = \rho_d e^{-h/H}. \quad (10)$$

Substituting this relationship into Eq. (9) gives

$$\begin{aligned} \rho_d &= \rho_f e^{h/H} \approx M/D_f^2 H = M/[k^2(\rho_f/\rho_a) h^2 H] \\ h^2 e^{h/H} &\approx M \rho_a / H \rho_f^2, \end{aligned} \quad (11)$$

where $M \approx \rho_a D^3/2$. Figure 4 shows the result of an iterative solution for h as a function of D and Z_f . Objects less than 1 m across drift less than 1 km for any fragmentation altitude. One meter objects that fragment at 30 km drift about 2 km; 4 m objects drift about 8 km. Even 4 m objects that fragment at 10 km only drift about 800 m. Thus, the drift phase is short for small and strong objects. The drift distance from fragmentation to deceleration increases roughly as $D^{3/2}$ and about a factor of 2 for each 5 km increase in Z_f . The reason for that can be seen by rearranging Eq. (11) to

$$h \approx h_0 e^{Z_f/H} e^{-h/2H} \quad (12)$$

where $h_0 = \sqrt{(D^3 \rho_a^2 / 2 H \rho_0^2)}$. If the second exponential can be ignored, which is the case except for both Z_f and D large,

$$h \approx h_0 e^{Z_f/H} \propto D^{3/2} e^{Z_f/H}, \quad (13)$$

as observed in Fig. 4.

Combined fragmentation and acceleration combines the two phenomena treated above by using Z_f from Eq. (5) in Eq. (12). The result is shown in Fig. 5, which indicates that the drift distance again increases roughly as $D^{3/2}$ and with object velocity as roughly V^2 . For 5 km/s objects the drift distance is less than 1 km. For 4 m 25 km/s objects it reaches about 10 km. The increases with D and V decrease at large D and V . The reason for this scaling can be seen approximately by substituting Eq. (5) in Eq. (12), which gives

$$h \approx h_0 e^{Z_f/H} e^{-h/2H} = h_0 (CV_0^2/S) e^{-h/2H} \quad (14)$$

For $h \ll 2H$, the scaling on $D^{3/2}$ and V^2 is explicitly shown. The points at the upper right where the D and V scaling saturate involve large h . The drift distance h can be subtracted from the fragmentation height Z_f to produce the approximate height of deceleration shown in Fig. 6. For low speeds, the altitude is about 10 km for all object sizes. For higher speeds, the deceleration altitudes decrease with object size. They are about 20 km for large objects for all $V > 15$ km. Their deceleration altitudes decrease to about 10 km for 20-30 m objects.

Power transfer to the flow field can be used as a surrogate for emitted radiation. The object's radiation rate when it is at an altitude where the density is ρ is approximately

$$P = K\rho AV^3, \quad (15)$$

where K is taken to be a constant here. Prior to breakup, the area A is fixed and the power scales as $\rho V^3 \propto \rho(V_0 e^{-\rho H/\beta})^3 \propto \rho e^{-3\rho H/\beta}$, which has a maximum at $\rho = \beta/3H$. After breakup, the rapid increase of A modifies this scaling. Using Eq. (8) for A gives

$$P_f = K\rho k^2(\rho_f/\rho_a) h^2(V_0 e^{-\rho H/\beta})^3 = Kk^2\rho(\rho_f/\rho_a) h^2 V_0^3 e^{-3\rho H/\beta}, \quad (16)$$

where $h = H \ln(\rho/\rho_f)$. Figure 7 shows the power from 4 m objects at 20 km/s, one of which is intact and the other of which fragments at 25 km. Fragmentation shifts the altitude of peak power up by about 15 km and reduces its width by about a factor of 3. The peak power is about the same for the two.

For constant area, it is possible to differentiate Eq. (15) with respect to ρ to show that the maximum power occurs at $\rho A = \beta/3H$. With fragmentation, that is not possible because β also varies with altitude. However, it is shown in Eq. (11) that the density at which deceleration takes place is approximately $\rho_d \approx M/[k^2(\rho_f/\rho_a) h^2 H]$, which agrees with the drift distance from Fig. 5 for these conditions. Using Eq. (9) gives the maximum power as approximately

$$P_f = (KM/H)V_0^3 e^{-3} = K\rho_a(DV_0)^3/2e^3 H, \quad (17)$$

which is shown in Fig. 8. For any D , P_f increases as V_0^3 . For any V_0 , P_f increases as D^3 . Since from Eq. (15) the peak power from non-fragmenting objects scales as $\rho AV^3 \propto (\beta/3H)D^2 V^3 \propto (DV)^3$, the peak power from fragmenting and non fragmenting objects would be about the same—if real objects could reach their altitudes of peak power before fragmenting.

Numerical results confirm these analytic predictions. Figure 9 shows numerical predictions for the power from intact and fragmenting objects as functions of altitude for 20 km/s entry of 4 m objects. Although the latter shows a slightly different normalization than Fig. 7, the rate of increase of power, rate of fall after peak, and the width of the power pulse are very similar. Thus, the analytic model does capture the primary features of the numerical calculations for this and other conditions. These correlations are pursued further in subsequent studies that incorporate the effects of ablation as well.

Inversion for fragmenting objects. These results can also be used to work backwards to infer the parameters of fragmenting objects from observations. The fundamental measurements are the peak power and altitude and the time from fragmentation to deceleration. The peak power determines the product of D and V_0

$$DV_0 \approx (2e^3 HP_f / K \rho_a)^{1/3}, \quad (18)$$

it does not determine them separately. However, from Eq. (9), $\rho_d H \approx \beta_d \approx 0.7 \rho_a D$, so the measurement of the altitude of deceleration determines

$$D \approx 1.3 H \rho_d / \rho_a, \quad (19)$$

which determines D . Its principal sensitivity is to ρ_a , which could be uncertain to a factor of two.

It might be determined more precisely, as discussed below. Eq. (18) can then be used for

$$V_0 \approx 0.7 (2e^3 \rho_a^2 P_f / K^2 H^2)^{1/3} / \rho_d. \quad (20)$$

Overall, $D \propto \rho_d$, and $V_0 \propto 1/\rho_d$, i.e., D decreases exponentially and V_0 increases exponentially with deceleration altitude. V_0 depends on the combination $(\rho_a^2 P_f)^{1/3}$, in which the dependencies are just strong enough for sensitivity. If Z_f is measured or the drift distance is inferred from the interval between the time of change in the light curve slope (fragmentation) and the time of peak radiation—i.e., $h \approx \text{interval}/\text{speed}$ —Eq. (12) can be used to estimate ρ_a or the angle of incidence for non-vertical entry. Since it is known that the object has fragmented from the change of slope and width and V_0 is determined above, Eq. (5) can be used to estimate the strength S and hence type of the object.

Summary and conclusions. This note discusses the breakup of non-ablating and ablating objects during entry. It uses the kinematic results of previous reports to describe the velocity and pressure of entering objects. It adds a mechanism for the breakup of objects during deceleration and a treatment of the further breakup and separation of fragments during their descent. It uses the constraint on mass per unit area derived earlier to determine the altitude and magnitude of peak power radiation. These results reduce to those derived earlier for strong objects in that limit. The model predictions are shown to be in agreement with the key features of numerical calculations of deceleration. It is shown that the model equations can be readily inverted analytically to infer object size, entry speed, and strength from measurements of peak power and altitude and fragmentation altitude or time.

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p vs z; Do

Fig. 1. Pressure as a function of altitude for 20 km/s entry of objects of various diameters (m).

Fig. 2. Maximum pressure versus object diameter for various entry speeds.

breakup alt vs S; Vo

Fig. 3. Approximate fragmentation altitude vs strength for various entry speeds.

drift dist vs D; Zbreak

Fig. 4. Approximate drift distance versus object diameter for various fragmentation altitudes (km).

Fig. 5. Approximate drift distance versus stony object diameter for various entry speeds.

decel alt vs D; V

Fig. 6. Approximate deceleration altitude versus object diameter for various entry speeds (km/s).

P vs z w/ & w/o frag

Fig. 7. Power versus altitude from 20 km/s intact object and one that fragments at 25 km.

Fig. 8. Maximum power versus diameter for fracturing objects for various entry speeds (km/s).

Pwr vs z

Fig. 9. Power versus altitude for 20 km/s intact and fragmenting objects.