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**FILTER FOR INTERPRETATION OF
FRAGMENTATION DURING ENTRY**

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FILTER FOR INTERPRETATION OF FRAGMENTATION DURING ENTRY

Gregory H. Canavan

Objects that fragment cascade and decelerate abruptly, producing short, bright, signatures which can be used to estimate object diameter and speed. Other objects can be incorporated into a generalized fragmentation filter.

Introduction. This note summarizes the results previous reports on the prediction and inversion of signatures from objects that radiate, ablate, and fragment during entry and uses them to produce models for the parameters of entering objects. It starts with detailed models that it uses to calibrate analytic models, which can be inverted to infer size and velocity.

Entering objects can be organized by the extent to which they radiate, ablate, and fragment. Objects that neither ablate nor fragment, still radiate, which can be predicted and inverted to infer object size and velocity accurately. This analysis can be extend to small objects that ablate but not fragment. Objects that fragment quickly cascade into debris that coheres and decelerates abruptly, producing bright and peaked, but still interpretable signatures. Ablation does not complicate these results because fragmentation produces deceleration at high altitudes.

Conditions for fragmentation are simple and robust. After fragmentation, debris spreads with a speed proportional to that of its parent object. The size of the cloud and its radiation rate, which are simply related to object diameter, can be calculated analytically. That permits a simple solution for object diameter and speed as functions of observable parameters. For a given peak power, object diameter increases and velocity decreases with pulse length. For given pulse length and peak power, object diameter decreases and velocity increases with altitude.

Ablating and non-ablating objects can be treated by a single filter, and ablation can be incorporated into fragmentation, so the appropriate filter discriminant is the light curve. Small and non-fragmenting objects have growth slower than exponential because they decelerate at high altitudes. Fragmenting objects have growth faster than exponential because their area increases rapidly. Objects that start with growth faster than exponential will produce, after fragmentation, many decelerating objects correlated with the flash of the parent body. Thus, the appropriate input to the bulk filter is the radiated energy, which is an indicator of the size and energy of the object. It would be desirable to use a more sophisticated matched filter, but the variety of shapes of light curves is such that a more sophisticated filter is not warranted.

Summary of previous analyses. The previous analyses can be organized by the extent to which entering objects exhibit radiation, ablation and fragmentation, which is the organization suggested by the first report in this series.¹

For objects that neither ablate nor fragment during entry, the principal observable is the radiation due to the fraction of their kinetic energy transferred to the flow field by drag.² The hydrodynamics of such objects can be solved and inverted essentially without approximation, so measurements of peak power, duration of radiation pulse, and altitude of maximum deceleration can be used to infer object size and velocity,³ to within the residual uncertainties in the treatment of radiation at high velocities and altitudes.^{4,5} These results can be used directly for the interpretation of iron meteorites; they can also be used to interpret the later development of special or slowed fragments.

For objects that ablate but do not fragment during entry, it is possible to extend the previous analysis to incorporate the ablative loss of mass during entry and the more rapid deceleration it causes.⁶ The resulting equation for the inferred object diameter contains an additional term proportional to the ratio of the object's kinetic energy and heat of vaporization, which can be solved by iteration for the object type, as well as size and speed. It reduces to the previous expression for objects with high heats of vaporization or low velocity, so it can be used to solve for all objects, as the non-ablative ones will be identified in the process. This solution is also appropriate for the 1-10 cm objects that form the bulk of observations, as the small size of these objects causes them to decelerate and ablate rather than fragment.

Objects that fragment but not ablate exhibit a cascade fragmentation into successively smaller pieces of debris, which cling together until decelerated abruptly by drag at a common altitude. That leads to an invertible solution that is considerably different than those of the previous cases.⁷ Rather than decelerating over a scale height or more, fragmenting objects can decelerate abruptly over a distance of a few kilometers, which produces light curves that are brighter and more peaked. However, the results are still interpretable with equations only slightly more complicated than those for the cases involving ablation.

Objects that both fragment and ablate are similar to objects that fragment but do not ablate, i.e., they largely reduce to the above case.⁸ The reason is that for objects that fragment, deceleration takes place at altitudes higher than those where significant ablation would take place. It can be significant during deceleration, but with cascade fragmentation, that takes place over a relatively short distance. Thus, the effect of ablation is a second order effect compared to those of fragmentation, drag, and radiation. The basic equations for fragmenting objects were given in earlier reports; their essential scaling and inversion are discussed further below.

Of the four combinations—ablating or non-ablating and fragmenting or non-fragmenting, the previous analyses have shown that the first two cases can be combined in a single filter that covers both ablating and non-ablating objects, and empirically most objects fragment. For fragmenting objects, ablation is second order, but it can be incorporated analytically, as there are some very strong objects, such as irons, that may not fragment, and some slow objects, such as

post-fragmentation debris, that no longer fragment. For them, the ablative model may be needed. Thus, it is necessary to have some bulk filter to differentiate between them.

The most appropriate filter is the object light curve. Integral objects have a light curve that increases exponentially in time, because they are proceeding at a roughly constant rate into air of exponentially increasing density, to which their radiation is proportional. Small, non-fragmenting objects have slower growth because they decelerate at high altitudes. Fragmenting objects have faster growth because they have rapidly growing areas in addition to the growth due to density. Thus, the growth rate of their light curve is the appropriate discriminant between the three possible types of objects, although in practice, it is only look for increasing or decreasing growth relative to exponential. Objects with the former will produce, after fragmentation, more decelerating objects that can be identified by the flash of the parent body. Objects with the latter will generally decelerate before they could fragment.

The appropriate input to the bulk filter is the energy radiated, i.e., the integral of the radiated power over the light pulse. It is a rough indicator of the size and energy of the object, thus, it can be reliably used to measure exceedences relative to whatever threshold provides the system false alarm rate thought to be tolerable. It would be desirable to use a more sophisticated matched filter than the simple integration of energy over a time period of ≈ 0.5 -1 s, but the variety of light curves is such that more sophisticated filter is not warranted by the data.^{9,10}

Fragmentation. Earlier notes established the rough criteria for breakup.¹¹ The ram pressure on the front of the object is

$$p \approx \rho V^2. \quad (1)$$

As the object descends, its velocity decreases, but the density increases, so the pressure has a maximum at some intermediate altitude, which is studied elsewhere.¹² Entering objects generally fragment when the increasing pressure exceeds the mechanical strength of the object, S , which in an exponential atmosphere of scale height H occurs at an altitude of

$$Z \approx -H \ln(S/CV^2). \quad (2)$$

Table 1 gives the strengths of objects according to their common classifications.

Table 1. Approximate meteor parameters.¹³

type	density(kg/m ³)	Q(MJ/kg)	S(N/m ²)	Z(km @ 20km/s)
iron	8000	8	10 ⁸	15
stone	3500	8	10 ⁷	30
carbon	2200	5	10 ⁶	45
cometary	1000	2.5	10 ⁵	60

Strengths range from $S = 10^8$ to 10^5 N/m²; thus, iron, stone, carbonaceous, and cometary objects with $V = 20$ km/s would fragment at altitudes of $\approx 15, 30, 45$, and 60 km, respectively.

Expansion. Pieces of debris expand rapidly after fragmentation, which increases their total effective area. That increases their drag, which causes them to decelerate. If the pressure on a fragment is larger than its strength, it will also fragment, which increases the total area still further. This cycle of fragmentation and deceleration can proceed through several generations until the fragments move too far apart to share a common shock or are decelerated enough to reduce the pressure below their material strength. That stops the cascade, after which fragments descend as separate objects.

It is possible to describe this deceleration somewhat more quantitatively. After breakup, the fragments move apart at a speed¹⁴

$$v \approx k\sqrt{(\rho/\rho_a)}V_0, \quad (3)$$

where ρ is the density at the breakup altitude and $k \approx 0.6$ is a constant chosen on the basis of dimensional and scaling arguments; various models use values of k from ≈ 0.6 to 2.¹⁵ The density of stony objects is $\rho_a \approx 3,000 \text{ kg/m}^3$ so breakup at $\approx 30 \text{ km}$ where $\rho \approx 0.01 \text{ kg/m}^3$ and $\sqrt{(\rho/\rho_a)} \approx 0.002$ would produce $v \approx 0.002 \times V \approx 30 \text{ m/s}$, which would cause a fragment shell to expand to a diameter ten times larger than its initial 1 m in $\approx 10 \text{ m} / 30 \text{ m/s} \approx 0.3 \text{ s}$.

In descending a distance h , the fragments expand to a diameter $\approx vh/V \approx k\sqrt{(\rho/\rho_a)}h$. When the area of the fragments reach an area A such that their areal density reaches $M/A \approx \rho H$, the decelerate abruptly, radiating strongly due to their large area.¹⁶

Total mass does not change rapidly during deceleration, for other than cometary objects, and density does not vary strongly because deceleration occurs over only a few kilometers, so the momentum of the fragment cloud evolves as¹⁷

$$Mdv/dt = -C\rho(D + vt)^2V^2, \quad (4)$$

where t is the time since fragmentation and $C \approx 1$ is the drag coefficient of the flattened debris.¹⁸ Equation (4) can be solved numerically; it also has the approximate solution

$$V = 1/L(K + y^3), \quad (5)$$

where $y = D + vt$,

$$L = NC\rho/3Mv = \sqrt{(\rho/\rho_a)}/bV_0D^3, \quad (6)$$

$$K = 1/LV_0 - D^3 = b(\sqrt{(\rho_a/\rho)} - 1)D^3, \quad (7)$$

where $b = 3k/2NC \approx 1$, V_0 is the initial velocity, and N is a parameter from the averaging of density and mass over cascade altitude. Since $\sqrt{(\rho_a/\rho)} \approx \sqrt{(3000/0.01)} \approx 550 \gg 1$, and $3k/2NC \approx 3 \times 0.6/2 \times 0.5 \times 1.7 \approx 1$, $K \approx 1/LV_0 \approx \sqrt{(\rho_a/\rho)}D^3$.

Figure 1 compares the approximate solution of Eq. (5) with the numerical solution of Eq. (4) for the breakup of a $D = 1 \text{ m}$ object with speed $V_0 = 15 \text{ km/s}$ at $Z = 26 \text{ km}$. $N = 0.5$ used provides an adequate match to both the initial slope and the rapid fall of the numerical curve. It underestimates the numerical curve for $V < 100 \text{ m/s}$, but such velocities are of little interest.

Equation (5) shows that if M is decreased or ρ increased, the velocity at any time would decrease. The erosion of M and of the increase of density during descent have just that effect. It is possible to use more careful approximations to M and more careful integrations over density to remove these errors; however, that is not necessary for an invertible approximation to the power radiated during maximum deceleration.

Figure 2 shows the variation of the approximate V with time from fragmentation for object diameters $D = 0.5, 1, \text{ and } 2 \text{ m}$. The former decelerates from 15 to 1 km/s by $\approx 0.3 \text{ s}$. The 1 m object decelerates to 1 km/s by $\approx 0.7 \text{ s}$, in agreement with Fig. 1. The 2 m object does not decelerate to 10 km/s until $\approx 0.35 \text{ s}$, in agreement with the numerical solution.

The radiation rate¹⁹ is $P = fpAV^3$, where $f \approx 0.1$ is the radiating efficiency (ratio of power radiated to that transmitted to the flow field by the object),²⁰ and A is the radiating area. The approximate radiation rate is

$$P = fp(D + vt)^2 V^3 = fpy^2/L^3(K + y^3)^3, \quad (8)$$

Figure 3 compares the numerical and approximate solutions for a $D = 1 \text{ m}$, 15 km/s object for the conditions above. The numerical value shown by the solid diamonds is about 20% above the approximate curve at their peak, but the two curves have about the same half width, so the total energy radiated by the two is within 10-20%. The discrepancy drops to a few percent at $V_0 = 20\text{--}25 \text{ km/s}$. The approximate curve is slightly lower for $P \ll 1 \text{ GW}$, but the contribution from there is negligible. Both curves show the radiation from a 26 km fragmentation peaks at about 23.5 km and falls to near zero by $\sim 22 \text{ km}$. That is radiation from fragmentation has a half width of only about 2 km rather than the 2-4 *scale heights* of frictional or ablative deceleration. It is difficult to perform accurate calculations of functions with such rapid variation even with numerical codes; thus, accurate analytic solutions are useful for scientific studies as well as the inversions below.

Figure 4 shows the variation of the approximate P with t for $D = 0.5, 1, \text{ and } 2 \text{ m}$ objects. The radiation for 0.5 m peaks at about 0.08 s at about 10 GW. That for 1 m peaks at about 0.15 s at 100 GW, and that for 2 m peaks at about 0.3 s at 350 GW. From Eq. (8), for $t \ll D/v$, $P \sim fpD^2V^3 \sim D^2$ in accord with the scaling seen at short time. For $t \gg D/v$, $P \sim 1/L^3y^7 \sim (VoD^3)^{3/7} L^3y^7 \sim Vo^3D^9/t^7$, which is consistent with the six order of magnitude difference in power seen at 0.8 s.

Peak power. Equation (8) for P can be differentiated with respect to y and the result equated to zero to find the value of y for which P is maximum, which is

$$y_{\max} = (2K/7)^{1/3} = (2/7)^{1/3}[(3k/2NC)(\sqrt{(\rho_a/\rho)} - 1)]^{1/3}D, \quad (9)$$

which is shown as a function of altitude in Fig. 5. $y_{\max}$ increases in proportion to D and exponentially with z . The latter follows from the result that generally $y_{\max} \gg D$, so that from Eq. (9), $y_{\max} \sim (\rho_a/\rho)^{1/6} \sim e^{z/6H}$, which is a straight line of slope $\sim 1/6H \sim 1/40 \text{ km}$ on an

exponential plot, in agreement with Fig. 5. Since the expansion velocity v is constant, the time from breakup to maximum power is

$$t_{\max} = [y_{\max} - D]/v = [(2K/7)^{1/3} - D]/v \approx (2K/7)^{1/3}/v, \quad (10)$$

which is shown in Fig. 6. For $D = 1$ m, $t_{\max}$ ranges from 0.02 at 10 km (which an object that small is unlikely to reach) to 1.2 s at 50 km. The times for 0.5 and 2 m are factors of 2 lower and higher. The curve for $t_{\max}$ is also straight because $t_{\max} \sim (2K/7)^{1/3}/v \sim (\rho_a/\rho)^{1/2}/(\rho/\rho_a)^{1/2} \sim 1/\rho$, which gives the ~ 7 km scale height seen. Substituting $y_{\max}$ from Eq. (9) into the P of Eq.

(8) gives an expression for the peak radiated power

$$\begin{aligned} P_{\max} &\approx f p y_{\max}^2 / L^3 (K + y_{\max}^3)^3 \approx f p (2K/7)^{2/3} / (1/V_0 K)^3 (K + 2K/7)^3 \\ &\approx [(2/7)^{2/3} / (9/7)^3] f p V_0^3 K^{2/3} \approx 0.2 f p V_0^3 [b(\sqrt{\rho_a/\rho} - 1)]^{2/3} D^2 \\ &\approx 0.2 b^{2/3} f p V_0^3 (\rho_a/\rho)^{1/3} D^2, \end{aligned} \quad (11)$$

which resembles the expression for the rate of radiation from a non-fracturing object multiplied by a factor of $(\rho_a/\rho)^{1/3} \approx 65$. Figure 7 shows $P_{\max}$ as a function of breakup altitude for $D = 0.5$, 1, and 2 m objects incident vertically at 20 km/s. $P_{\max} = \rho^{2/3}$, so it falls exponentially with altitude with a scale height $\approx 2/3 H$. A 1 m object has a peak power of ≈ 200 GW at 25 km, which is an order of magnitude higher than if it fragmented at 50 km. The curves for 0.5 and 2 m objects lie factors of 4 below and above that for 1 m.

Inversion for fragmenting objects. The principal observables of entry are $P_{\max}$, $t_{\max}$, and the fragmentation altitude Z . If they are known, the above results can be inverted to infer the parameters of fragmenting objects from observations. When Z is known, the density dependent terms become constant coefficients in $q(Z) = \sqrt{[\rho_a/\rho(Z)]}$, and

$$\begin{aligned} t_{\max} &\approx (2K/7)^{1/3}/v \approx (2/7)^{1/3} [b q D^3]^{1/3} / k V_0 / q \\ &\approx 0.7 b^{1/3} q^{4/3} D / k V_0. \end{aligned} \quad (12)$$

This time to maximum power shown in Fig. 6, which is also an effective radiation half width, can be used to express V_0 in terms of D and $t_{\max}$ as

$$V_0 \approx 0.7 b^{1/3} q^{4/3} D / k t_{\max} \quad (13)$$

The expression for $P_{\max}$ thus becomes

$$P_{\max} \approx 0.2 b^{2/3} f V_0^3 \rho_a (\rho^2/\rho_a^2)^{1/3} D^2 \approx 0.2 f (0.7 b^{1/3} q^{4/3} D k / t_{\max})^3 \rho_a D^2 / q^{4/3}, \quad (14)$$

so that

$$D \approx [17 k^3 t_{\max}^3 P_{\max} / f \rho_a q^{8/3} (3k/2NC)^{5/3}]^{1/5}, \quad (15)$$

which scales most strongly on $t_{\max}^{3/5}$ and less strongly on $P_{\max}^{1/5}$. Figure 8 shows D vs $t_{\max}$ for fragmentations at 30 km altitude with $P_{\max}$ from 100 to 10,000 GW. As $t_{\max}$ increases from 0.075 to 0.7 s for a given $P_{\max}$, the inferred diameter D increases by about a factor of 4. At 1,000 GW, it increases from 0.9 to 3.2 m. For a given $t_{\max}$, D increases about a factor of three for this range of $P_{\max}$. At $t_{\max} \approx 0.3$ s it increases from ≈ 1.3 to 3 m.

Figure 9 shows the variation of V_0 with $t_{\max}$ for the same values of $P_{\max}$, which is weaker. For 1,000 GW the velocity decreases from ≈ 40 to 18 km/s. The velocities for powers 10-fold larger and smaller are 2-fold larger and smaller. Figure 10 shows the object tensile strengths corresponding to the conditions of Figs. 8 and 9, computed from Eq. (1). For 1,000 GW, S falls from ≈ 400 to 70 bar as $t_{\max}$ increases from 0.7 to 7 s. Table I indicates that fragmentations at 30 km with $t_{\max} \approx 0.1$ s would have $S \approx 1,000$ bar, corresponding to iron objects; those with $t_{\max} \approx 0.3$ s increases would have $S \approx 100$ bar, corresponding to stony objects; and those with $t_{\max} \approx 0.1$ s would have $S \approx 10$ bar, corresponding to carbonaceous objects. Cometary objects would fragment at higher altitudes.

Figure 11 shows the variation of D with z for $t_{\max} = 0.1$ to 1 s and $P_{\max} = 1$ TW from 10 to 70 km—although the analytic model is intended to be accurate primarily for the impacts below 50 km seen by satellite sensors. For 0.3 s, 10 km fragmentation would indicate a 4 m object. $t_{\max} = 0.1$ and 1 s would indicate 2 and 9 m objects. For $t_{\max} = 0.3$ s, fragmentation at 30 km would indicate a 2 m object, as above. Fragmentation at 45 km would indicate a 1.2 m object, and fragmentation at 60 km would indicate a 0.6 m object, as above.

For the noisy and structured power curves, it is sometimes difficult to determine the half width more precisely than ≈ 0.1 s, which corresponds to about a factor of two uncertainty in D . The sensors with good time resolution cannot generally determine the altitude of fragmentation more precisely than about a scale height, which for a given $P_{\max}$ corresponds to about a factor of 1.5 in D . Thus, the error bars in the inversions are not insignificant simply due to the resolution limitations of the sensors on which they are based.

Summary and conclusions. This note uses the results previous reports on the prediction and inversion of signatures from objects that radiate, ablate, and fragment during entry to produce estimates of the parameters of entering objects, which are calibrated with the predictions of more detailed models.

Entering objects can be organized by the extent to which they radiate, ablate, and fragment. For objects that neither ablate nor fragment, the principal observable is radiation, which can be predicted and inverted to within uncertainties in the treatment of radiation at high velocities and altitudes, so measurements of peak power, radiation pulse width, and altitude of maximum deceleration can be used to infer object size and velocity accurately. For small objects that ablate but not fragment, the analysis can be extend to incorporate the more rapid loss of mass and deceleration it causes during entry. They contain non-ablating objects as a sub-set that are identified by the solution.

Objects that fragment exhibit cascade fragmentation into debris that coheres and decelerates abruptly, which produces light curves that are brighter and more peaked, but still interpretable with equations slightly more complicated than those for ablation. Objects that both

fragment and ablate produce similar observables because fragmentation produces deceleration at altitudes higher than those where significant ablation would take place. Thus, ablation is a second order effect compared to fragmentation, drag, and radiation.

The condition for fragmentation is that ram pressure equal material strength. After fragmentation, the debris spreads with a speed a fraction of a percent of the parent object speed. The size of the cloud can be calculated analytically, as can the radiation rate. That determines the peak power and radiation pulse width as functions of object diameter, which permits a simple solution for the object diameter and speed as functions of observable parameters. For a given peak power, the object diameter increases and velocity decreases with pulse length. For given pulse length and peak power, object diameter decreases and velocity increases with altitude. These relationships are in a form suitable for both inversions, as well as sensitivity assessments.

Ablating and non-ablating objects can be treated by a single filter, and are dominated by that for fragmenting objects, so the appropriate filter discriminant is the light curve. Small and non-fragmenting objects have growth slower than exponential; fragmenting objects have faster growth. Objects that start increasing growth relative to exponential will produce, after fragmentation, more decelerating objects that can be correlated with the flash of the parent body. The appropriate input to the bulk filter is their radiated energy, which is a rough indicator of the energy and size of the parent object. It would be desirable to use a matched filter, but the variety of light curves is such that a more sophisticated filter is not warranted by the data.

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Fig. 1. V & Vaprr vs height

V t

Fig. 2. V vs time for various D (m)

Fig. 3. Power vs altitude

Fig. 4. Power vs time for various D (m)

Fig. 5. Ymax vs altitude for D (m)

tmax v z

Fig. 6. Tmax vs altitude for D (m)

Fig. 7. Pmax vs altitude for D (m)

8 D v tm

Fig. 8. D vs tmax for Pmax (GW)

Vo v tm

Fig. 9. Vo vs tmax for Pmax (GW)

Fig. 10. S vs tmax for Pmax (GW)

Fig. 11. D vs z for 1 TW & tmax(s)

Fig. 12. V vs z for 1 TW & tmax(s)

Fig. 13. Strength vs z for 1 TW & tm(s)