Atmospheric Energy Deposition Modeling and Inference for Varied Meteoroid Structures

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Abstract

Asteroids populations are highly diverse, ranging from coherent monoliths to loosely bound rubble piles with a broad range of material and compositional properties. These different structures and properties could significantly affect how an asteroid breaks up and deposits energy in the atmosphere, and how much ground damage may occur from resulting blast waves. We have previously developed a fragment-cloud model (FCM) for assessing the atmospheric breakup and energy deposition of asteroids striking Earth. The approach represents ranges of breakup characteristics by combining progressive fragmentation with releases of variable fractions of debris and larger discrete fragments. In this work, we have extended the FCM to also represent asteroids with varied initial structures, such as rubble piles or fractured bodies. We have used the extended FCM to model the Chelyabinsk, Benešov, Košíce, and Tagish Lake meteors, and have obtained excellent matches to energy deposition profiles derived from their light curves. These matches provide validation for the FCM approach, help guide further model refinements, and enable inferences about pre-entry structure and breakup behavior. Results highlight differences in the amount of small debris vs. discrete fragments in matching the various flare characteristics of each meteor. The Chelyabinsk flares were best represented using relatively high debris fractions, while Košíce and Benešov cases were more notably driven by their discrete fragmentation characteristics, perhaps indicating more cohesive initial structures. Tagish Lake exhibited a combination of these characteristics, with lower-debris fragmentation at high altitudes followed by sudden disintegration into small debris in the lower flares. Results from all cases also suggest that lower ablation coefficients and debris spread rates may be more appropriate for the way in which debris clouds are represented in FCM, offering an avenue for future model refinement.

1. Introduction

Simplified semi-analytic models of how meteoroids decelerate, ablate, and break up and during atmospheric entry are used to assess ground damage due to potential asteroid impacts [Mathias et al., 2017; Stokes et al., 2003, 2017; Collins et al., 2005; Rumpf et al., 2016], to study aspects of meteor physics or fragment dynamics [e.g., Artemieva & Shuvalov, 2001; Borovička & Kalenda, 2003], and to make inferences about the properties of observed meteors [e.g., Brown et al., 2002; Borovička et al., 1998]. These types of models—which have alternately been called analytic, semi-analytic, single-body, or numerical models—integrate similar variants of the standard meteor physics equations [Opik, 1958; Bronshten, 1964; Baldwid & Sheaffer, 1971] to compute the motion and ablation of a body throughout its atmospheric entry, employing various simplified approaches to represent the breakup process. Typically, the breakup process is
approximated either by treating the body as a single deforming mass (often called a pancake or liquid drop approach) [Hills & Goda, 1993; Chyba et al., 1993; Melosh, 1981], or as a progressive subdivision of individual fragments [ReVelle, 2005, 2007]. However, these approaches assume uniform asteroid compositions and fragmentation rates, and so are unable to represent the broad variations in realistic asteroid structures, which could range from strong coherent monoliths to loosely bound rubble piles [Britt et al., 2002; Richardson et al., 2002]. These structural variations could significantly affect how the object breaks up and deposits its energy in the atmosphere, as evidenced by the diversity of light curve profiles and flare features among observed meteors.

We present results of our updated fragment-cloud model (FCM) approach [Wheeler et al. 2017], which we have now extended to represent a variety of non-uniform asteroid structures such as rubble piles or fractured bodies. This extension enables the model to reproduce a broad range of realistic flare features seen in observed meteor light curves. We have used the approach to model the Chelyabinsk, Košice, Benešov, and Tagish Lake meteors, and have obtained excellent matches to energy deposition profiles derived from their light curves. The FCM results fall well within the uncertainty of the observationally derived energy deposition curves and are also able to reproduce many of the more detailed flare features. We have used these matches to make inferences about the potential pre-entry asteroid properties and their breakup characteristics, and also to assess modeling assumptions and parameter values. The objective of the FCM approach is to incorporate enough fidelity and variability to produce a realistic range of breakup characteristics, while also remaining simple and efficient enough to analyze the numerous cases needed to explore potential structural and property variations, match detailed light curve features, or perform probabilistic risk assessments.

2. Extension of the Fragment-Cloud Model to Varied Structures

The fragment-cloud model (FCM) approach represents the breakup process using a combination of discrete fragments and aggregate clouds of debris. The fragment components are used to represent coherent chunks that are large enough to be treated independently, while the cloud components represent the remaining smaller debris that is more influenced by common group aerodynamics and can be treated as an aggregate mass. The fragments each undergo a successive series of fragmentations, based on the triggered progressive fragmentation approach of ReVelle [ReVelle 2005, 2007]. In this approach, a break is triggered when the stagnation pressure exceeds the aerodynamic strength of the fragment (\(\rho_d\alpha v^2 > S\)) and the strengths of the child fragments increase relative to their decreased size with a Weibull-like scaling relation (\(S_f = S_0 \left( \frac{m_0}{m_f} \right)^\alpha \)) [Weibull, 1951; Bland & Artemieva, 2006]. In the FCM, however, the fragments can break into multiple sub-fragments with different mass fractions, rather than just two even pieces, and a fraction of the remaining mass is released as a debris cloud with each break event. The debris clouds are each treated as an aggregate mass that spreads and slows under a common bow shock, based on the pancake approach of Hills and Goda [Hills & Goda, 1993]. In this approach, the cross-sectional area of the debris cloud increases with a dispersion rate that is a function of the velocity, air density, material density, and a constant dispersion coefficient (\(C_{disp}\)).
All components are modeled until they ablate completely or reach the ground, and the energy deposition is computed as the total change in kinetic energy of all components per unit of altitude, typically expressed in kilotons per kilometer. The variable fragmentation parameters in FCM include the number and mass distribution of fragments produced in each break, the fraction of mass going into a debris cloud with each break, the fragment strength-scaling exponent ($\alpha$), the cloud dispersion coefficient ($C_{disp}$), and the ablation coefficient ($\sigma$) for the fragment and cloud components. Details of the FCM approach, its equations, and the effects of its various parameters on energy deposition are published in Wheeler et al. (2017). Comparisons of the combined fragment-cloud approach with other existing progressive fragmentation or pancake/liquid-drop approaches were performed during initial model development and are presented in Register et al. (2017).

In the current work, we have now extended the FCM approach to be able to represent a range of initial asteroid structures, including coherent monoliths, fractured bodies, regolith layers, or rubble piles. For non-uniform structures, the initial body can be comprised of different groups of rubble or pre-fractured fragments of a given size, plus a remaining fraction of debris. The numbers and masses of identical pre-fractured or rubble fragments in each structural group can either be specified individually, or can be set using inverse power law distributions. Each structural group can also be assigned different densities, strengths, and fragmentation parameters to represent their potentially different material properties. The aerodynamic breakup strengths of the structural groups can either be specified directly or based on their relative size using Weibull-like scaling. Each group can be comprised of a single fragment or divided into any number of identical fragments, all with the same size and fragmentation properties. When the aerodynamic stagnation pressure exceeds the aerodynamic strength of the initial body, the structural fragments are disrupted and are assumed to separate, and any initial debris is released as a cloud mass. The rubble fragments then continue descent until they begin their own fragment-cloud breakup process according to the initial strength and fragmentation parameters given to their group. Figure 1 shows a diagram summarizing the equations, breakup process, and various types of initial structures used in the extended FCM approach. Note that we generally refer to the structural fragments as “rubble” in describing our results, though they may also represent components of a pre-fractured body and do not necessarily imply that the initial body had a loose “rubble pile” structure before breakup.
3. Modeling the Breakup of Observed Meteoroids

Combining the FCM approach with varied initial structures has enabled us to obtain excellent matches to energy deposition profiles for a variety of observed meteoroids. In the following section, we present FCM results for the Chelyabinsk, Košice, Benešov, and Tagish Lake meteors. These cases span a diverse range of sizes and breakup features, including multiple flares of very different sizes, forms, altitudes, and cadences.

A number of other semi-analytic breakup models have also previously been used to assess various aspects of the Chelyabinsk, Košice, Benešov, and Tagish Lake meteor events by matching observed light curve, kinematics, or fragmentation data. For Chelyabinsk, Brown et al. (2013) applied the triggered progressive fragmentation model (TPFM) of ReVelle (2007) to constrain energy estimates for the event. Popova et al. (2013, supplement) applied a hybrid style approach—with both discrete fragments and cloud components, notionally similar to FCM—to model the Chelyabinsk light curve and energy deposition. However, the details of the model and its implementation were not presented, and results focused on estimates of meteorite falls, ablated mass, and luminous efficiency rather than pre-entry properties.

For Benešov, Borovička et al. (1998) also applied the gross-fragmentation model [Ceplecha, 1993] and a radiative radius approach [Nemchinov et al., 1997] to reproduce the light curve and provide estimates of initial mass and density. They also further applied combinations of progressive fragmentation and liquid-like/pancake approaches to represent select parts of the breakup, resolve discrepancies between photometric and dynamic mass estimates, and

**Figure 1.** Diagram of the fragment-cloud model approach, extended to represent various initial asteroid structures. In these equations, \( m \) is the mass, \( v \) is velocity, \( \theta \) is flight angle relative to horizontal, \( h \) is altitude, \( t \) is time, \( \rho \) is density, \( \sigma \) is the ablation coefficient, \( A \) is cross-sectional area of the body, \( C_D \) is the drag coefficient, \( g \) is gravitational acceleration, \( R_E \) is the radius of the Earth, \( S \) is aerodynamic strength, \( \alpha \) is the strength scaling coefficient, \( v_{\text{disp}} \) is the dispersion velocity for the lateral spread of the debris cloud radius, and \( C_{\text{disp}} \) is the dispersion coefficient.

- **Flight integration:**
  
  \[
  \frac{dm}{dt} = -0.5 \rho_{\text{air}} v^2 A \sigma \\
  \frac{dv}{dt} = \rho_{\text{air}} v^2 A C_D \frac{m - g \sin \theta}{m} \\
  \frac{d\theta}{dt} = \frac{v(R_E + h) - g v \cos \theta}{v^2} \\
  \frac{dh}{dt} = v \sin \theta
  \]

- **Fragmentation condition:**
  \[
  \rho_{\text{air}} v^2 > \text{Strength (S)}
  \]

- **Fragment strengths increase with decreased size**
  \[
  S_{\text{child}} = S_{\text{parent}} \left( \frac{m_{\text{parent}}}{m_{\text{child}}} \right)^{\alpha}
  \]

- **Clouds broaden and slow under common bow shock**
  \[
  v_{\text{disp}} = v_{\text{cloud}} \left( C_{\text{disp}} \frac{\rho_{\text{air}}}{\rho_{\text{debris}}} \right)^{1/2}
  \]
demonstrate the role of severe early fragmentation. Ceplecha and ReVelle (2005) later used their FM fragmentation model to match the Benešov light curve (among others) and assess the significance of fragmentation effects in ablation and luminosity modeling. ReVelle (2007) also applied the TPFM approach to Benešov, Tagish Lake, and several other bolides to develop improved estimations of terminal mass. More recently, Borovička (2015) also investigated evidence of potential early disruption/fragmentation for the Benešov and Chelyabinsk meteoroids, based on the dynamics, spectra, and light curve flares, to address the question of whether they may have been rubble piles.

For Košice, Borovička et al. (2013a) applied a selected mixture of various FM fragmentation modeling approaches (including discrete progressive fragmentations, dust particle swarms, and gradual erosion) to match the details of the light curve, evaluate the varied breakup mechanisms at play, and estimate the resulting numbers and masses of meteorites.

For Tagish Lake, Brown et al. (2002) applied the gross-fragmentation approach of Ceplecha et al. (1993) and a porosity ablation model approach [ReVelle, 2001] to match the light curve and estimate the masses of the initial body and surviving meteorites. Hildebrand et al. (2006) employed a similar approach to estimate meteorite locations as a function of size and fragmentation altitude. Ceplecha (2007) also applied the FM fragmentation model [Ceplecha and ReVelle, 2005] and prior gross fragmentation model [Ceplecha et al., 1993] to Tagish Lake to investigate the fragmentation history and assess intrinsic ablation and luminous efficiency values.

These prior modeling results have demonstrated the utility of matching simplified breakup models to observed light curve and kinematic data, and have contributed notably to the understanding of these meteor events and modeling factors. However, they have generally either only matched very general aspects of the light curve or dynamics, or have achieved more detailed matches by prescribing specific fragmentation events at selected breakpoints along the observed entry. With the exception of the rubble pile considerations in Borovička (2015), much of the prior modeling focus has also been on inferring down-stream meteorite masses and strewn fields rather than the initial pre-entry asteroid properties. In developing the FCM approach, we aim to further these types of observational inference capabilities, focusing on aspects of pre-entry structural makeup, how potential structural variations affect atmospheric energy deposition (which is most relevant to damage and risk assessment), and how to effectively model the key processes in a systematic, broadly applicable manner. To this end, our modeling is currently done in terms of energy deposition estimates rather than light emission, and the breakup is modeled solely from inputs defining the initial structural groups and FCM fragmentation parameters. The resulting energy deposition is computed using consistent application of the FCM breakup formulas throughout, without tuning any specified breaks or modifications along the trajectory.

4. FCM Results for Observed Meteoroids

To model the observed meteoroids presented here, we began with published estimates of the initial entry properties (size, mass, density, velocity, and entry angle), and then varied the initial asteroid structure and FCM fragmentation parameters to qualitatively match the magnitudes,
altitudes, and form of the energy deposition profile derived from the observed light curve data. For each modeled case, all parameters are set as initial inputs and are not specifically tuned along the entry. Note that the individual solutions are not necessarily unique, and different ranges or combinations of the various input parameters can produce comparably good matches to the energy deposition profile. To glean potential inferences from these non-unique solutions, we explore numerous parameter variations, look for the common trends among the family of best matches, and note when certain parameters are not necessarily well constrained by the results. The following results presented for each meteoroid show a sample of one of the best fits obtained, along with a discussion of the more generalized parameters ranges found across the various cases. The FCM integration is performed using 10-m altitude steps, and the energy deposition results are plotted at a 1-km resolution for comparisons with the observationally derived curves.

4.1 Chelyabinsk

Figure 2 shows an FCM match obtained for the Chelyabinsk meteoroid, which is estimated to have had an initial diameter of around 19.8 m, an entry velocity of 19.16 km/s, and entry angle of 18.3 degrees [Popova et al., 2013]. The Chelyabinsk energy deposition curve was adopted from Brown et al. (2013), who derived the estimate from the observed light curve assuming a blackbody emission of 6,000 K and bolometric luminous efficiency of 17%. Upper and lower bounds were also included, based on a bounding luminous efficiency range of 13-21% [Brown et al., 2013; Popova et al., 2013].

![Figure 2](image-url)
piece, and the last (rightmost) dot gives the total mass of the combined rubble group (though some groups contain only one single rubble piece).

In reproducing the Chelyabinsk energy deposition curve with FCM, we found that using the published meteorite-based density estimate of 3,300 kg/m$^3$ [Popova et al., 2013] as the bulk meteoroid density consistently exceeded the peak energy deposition by around 50% (123 vs. 83 kt/km observed). Reducing the bulk density and associated mass of the initial asteroid body down to around 2,200–2,600 kg/m$^3$ (while maintaining the meteorite-based material density for the rubble fragments) produced better matches. Relative to the meteoritic density, that translates to a macroporosity of around 21–33%, which is consistent with estimated ranges for a moderately fractured body (15–25% porosity) or a compact rubble pile (30–70% porosity) [Britt et al., 2002]. Borovička et al. (2013b) concluded that Chelyabinsk was a fractured stone and not a rubble pile, based on the very low (~25 kPa) rubble pile strength estimates of Sanchez & Scheeres (2014). However, the behavior of different asteroid structures under an entry bow shock is not very well characterized. Hydrocode simulations of asteroid entry have indicated that even very low-strength objects (~10 Pa) can remain largely intact to moderate altitudes [Robertson & Mathias, 2017], and quasi-liquid hydrocode simulations modeling the Chelyabinsk meteoroid as a strengthless object have reasonably reproduced the observed data [Shuvalov et al., 2017].

The results also provide insight into how different structures or different breakup characteristics can produce the observed flare features. The upper flare was well-reproduced by a debris cloud of ~0.2–0.3% of the initial asteroid mass, released at around half a megapascal (~0.5–0.6 MPa) of pressure. This debris may be indicative of an initial high-altitude blow-off of an outer regolith layer, or may represent the release of interstitial particulates as weakly bound rubble or fractured components begin minor disruption. Alternatively, the upper hump could also be reasonably modeled by the release of a small, weak fragment of ~0.25% of the initial bolide mass, beginning breakup at around 0.6 MPa and fragmenting rapidly with a low strength scaling exponent ($\alpha\lessgtr 0.1$) and high cloud mass fraction (75%). This type of feature could not be reproduced using the uniform structural assumptions and uniform fragmentation approaches utilized in our prior version of FCM, as was noted in the Chelyabinsk comparison presented in [Wheeler et al. 2017]. Borovička et al. (2013b) associated the Chelyabinsk upper flare with around 1% of the mass lost in the form of small fragments with masses of ~1,000 g, based on their fragmentation modeling approach [Borovička et al., 2013a]. With the current FCM approach, however, inclusion of debris clouds, either from the initial body disruption or from the successive breakup of a fragment, was needed in order to produce the small, distinct flare. Popova et al. (2013) found breakup initiating at a similar but slightly lower dynamic pressure of 0.2 MPa.

In modeling the main flare, around 95% of the initial asteroid mass undergoes catastrophic, successive fragmentation, beginning at around 1.4–1.6 MPa of aerodynamic stagnation pressure. To produce the broad, smooth profile of the main flare, the breakup was modeled with a large fraction of the mass (75–85%) being released as debris clouds with each fragmentation event. Lower debris mass fractions produced narrower, steeper-sloped profiles. This suggests that much of the material disintegrated readily into small debris that decelerated rapidly and could be effectively modeled in an aggregate fashion. Inclusion of 10–30 smaller rubble pieces with a range of sizes (~0.1–0.3% of the bolide mass) and initial aerodynamic strengths of 1.75–3.5 MPa also helped to produce the rounder upper edge of the flare. These findings are consistent with
those of Borovička et al. (2013b), who computed a similar proportion of mass (~95%) to be ablated in the main flare with small resulting fragments of under 1 kg [Borovička et al., 2013b, supplement].

The lower, secondary flare was best reproduced using rubble pieces with high enough initial strengths to penetrate below the main flare before beginning breakup. These stronger rubble pieces comprised around 2.5% of the initial mass, and began fragmenting at around 15.5 MPa of stagnation pressure. The lower flare could also be reproduced from successive fragmentations persisting below the main flare by applying a relatively high strength-scaling exponent of around 0.3–0.5, as was shown using the previous version of FCM [Wheeler et al. 2017], but this approach did not provide as strong a match as the rubble structure. The width of the secondary flare was fairly sensitive to the mass distribution of the fragments, and was best reproduced using two-fragment mass splits that were close but not exactly even (around 60/40% splits). Breakup into many smaller or more unevenly sized fragments yielded sharper flares that tended to separate from each other and did not match the observed flare width as well. Borovička et al. (2013b, supplement) and Popova et al. (2013, supplement) similarly found this flare to be associated with relatively large fragments. Although these rubble pieces remained intact up to large stagnation pressures, they required more rapid fragmentation—modeled with a low strength scaling exponent ($\alpha \sim 0.07$) and a high cloud mass fraction (~75%)—in order to reproduce the observed flare without producing additional fragmentation flares or excessively large surviving fragments below. This may indicate that their deeper penetration may have been partially due to shielding from other leading fragments rather than significantly higher inherent strength.

In addition to matching the energy deposition, the FCM rubble pile results also give reasonable matches to landed mass estimates from the discovered Chelyabinsk meteorite falls. The cases discussed here yielded total fallen fragment masses of around 5,000–6,500 kg (0.05–0.064% of the initial mass), compared to 4,000–6,000 kg (0.03–0.05% initial mass) estimated in Popova et al. (2013). Although we have not specifically developed the model to predict landed masses and have yet to more thoroughly investigate and test this capability, these ball-park landed mass comparisons can help to guide selection of the most representative fits among cases that produced similar energy deposition features. The match shown in Figure 2 yielded a total landed mass of 5,600 kg, with individual meteorite masses ranging from 9 g to around 340 kg.

It is also interesting to note that a disproportionate amount of the fallen meteorite mass in this case originated from the rubble group that began the first high-altitude breakup at around 45 km altitude. This group comprised only 0.25% of the initial bolide mass, but contributed around 50% of the total fallen meteorite mass. Over 18% of the group’s initial mass survived to the ground as meteorites, with masses ranging from 9 g to 340 kg. In comparison, the largest rubble group that formed the bulk of the main flare began with 93% of the initial bolide mass but contributed only 40% of the meteorite mass (0.04% of the group mass surviving to the ground), and the group forming the lower secondary flare contributed only around 9% of the meteorite mass from 2.4% of the initial bolide mass (0.4% surviving to the ground). The disproportionate amount of meteorite mass coming from the highest altitude fragmentations is notionally congruent with radionuclide results from Provinec et al. (2015), which indicated that 9 of the 12 analyzed Chelyabinsk meteorites likely came from within 1.8 m of the surface. Although the current FCM implementation does not specifically place rubble groups within the bolide volume, groups that
fragment first, at higher altitudes are conceptually more likely to represent material from the outer layers or frontal regions. Assuming a uniform average bulk density and 19.8 m spherical bolide shape, the mass fraction of the first rubble group, which contributed 50% of the meteorite mass, would equate to an outer spherical shell less than 1 cm thick, or a spherical cap with a dome depth of around 0.6 m.

Finally, our FCM matches for Chelyabinsk have also helped to identify modeling parameter assumptions that may warrant refinement or may vary among different asteroids. In particular, we found that reducing the ablation coefficient and the debris cloud dispersion coefficient by around a factor of two or more from the initially adopted baseline values helped to better match the broad, rounded width of the main peak. Using the initial baseline dispersion coefficient of 3.5 and ablation coefficient of $1 \times 10^{-8} \, \text{kg/J}$, both adopted from the Hills & Goda (1993) pancake model, produced narrower, sharper flare profiles that were difficult to broaden using other fragmentation parameters. The best matches were produced using dispersion coefficients of 1.5–2.5 and ablation coefficients of $4 \times 10^{-9}$ to $8 \times 10^{-9} \, \text{kg/J}$. These parameter trends were also noted in the Chelyabinsk modeling performed with the prior version of FCM [Wheeler et al., 2017], but remain applicable when variable rubble structures are included. These ablation coefficient values agree reasonably with the low end of the $5 \times 10^{-9}$ to $3.5 \times 10^{-7} \, \text{kg/J}$ range that Borovička et al. (2013b) derived from the dynamics of observed Chelyabinsk fragments, but are 2–4 times smaller than the $1.6 \times 10^{-8} \, \text{kg/J}$ value used in Popova et al. (2013). Use of reduced ablation coefficient values is also supported by recent aerothermodynamic CFD simulations of meteoroid entries with chemically reacting flows and coupled radiation and ablation [Johnston et al., 2018 in press]. Those simulations found heat transfer coefficient ($C_H$) values below 0.045, corresponding to ablation coefficient ($\sigma = C_H/Q$) values of around $1 \times 10^{-9}$ to $5.5 \times 10^{-9} \, \text{kg/J}$ for $Q$ around 8 MJ/kg.

4.2 Košice

Figure 3 shows a match obtained for the Košice meteoroid, which was estimated have an initial mass of around 3,500 kg, entry velocity of 15 km/s, and entry angle of 60° from horizontal [Borovička et al., 2013a].
Figure 3. An FCM energy deposition match for the Košice meteoroid, using four structural groups. The plot on the left shows the FCM energy deposition results compared with estimates derived from the observed light curved, assuming an initial mass of 3,500 kg for the nominal solid line and a factor-of-three range (1,170–10,500 kg) for the dashed uncertainty bounds [Borovička et al., 2013a]. The plot on the right shows a breakdown of the structural groups used for this match, with dots representing each individual rubble, sized by relative diameter and colored by relative mass. The identical rubbles in each group are aligned at the altitude where they begin breakup, with the corresponding breakup strength/pressure shown along the right axis. The horizontal axis shows the cumulative mass of the rubbles for each group, such that the first (leftmost) dot gives the individual mass of each identical rubble piece, and the last (rightmost) dot gives the total mass of the combined rubble group. The topmost rubble group for this match contains 300 pieces, while the other three groups each have one single piece.

Unlike for Chelyabinsk, there are limited observations of energy deposition for the Košice meteoroid. We computed an energy deposition curve using the meteor light curve published by Borovička et al. (2013a). First, the power radiated by the meteor as a function of time was computed by assuming that a zero-magnitude meteor radiates 1,530 W in the detector passband [Cepela & ReVelle, 2005]. Next, the total energy radiated by the meteor, $2.6\times10^{-3}$ kt, was computed by integrating the power radiated over the entire meteoroid trajectory. The initial kinetic energy of the meteoroid, 0.09 kt, was computed using an initial mass of 3,500 kg derived by the model of Borovička et al. (2013a), and the initial speed of 15.0 ± 0.3 km/s. An integrated, average luminous efficiency of 2.8% was computed by taking the ratio of total radiated energy to initial kinetic energy, which was consistent with the range of 2.5–5% estimated by Borovička et al. (2013a). The energy deposition, per unit time, was derived from the radiated power by dividing that curve by the integrated luminous efficiency. Similarly, the energy deposition per unit height, Figure 3, was found by dividing the deposition per unit time by the vertical speed of the meteoroid (the derivative of $h(t)$).

Borovička et al. (2013a) cautioned that the initial mass estimate for the Košice meteoroid was uncertain within a factor of three due to uncertainties in the light curve. This corresponds to an initial meteoroid kinetic energy between 0.031 and 0.28 kt. For comparison, Borovička et al. (2013a) estimated a total energy deposition of 0.15 – 0.24 kt based on infrasonic analysis, independent of light curve observations. Two dashed curves in Figure 3 show the energy
deposition corresponding to the factor-of-three mass bounds (1,170-10,500 kg), while the solid line shows the deposition corresponding to an initial mass of 3,500 kg.

It should also be noted that the energy deposition curve was prepared assuming a constant luminous efficiency. This is not expected to be the case, as luminous efficiency may vary with speed, meteoroid mass, and atmospheric density [ReVelle & Ceplecha, 2001; Ceplecha & ReVelle, 2005]. Intuitively, it is expected that the luminous efficiency would be smaller at larger heights, where rapid ablation is not occurring, and towards the end of the meteor, where the meteoroid has been decelerated. As a result, the emphasis was on modeling the behaviour near the peaks of the energy deposition curves.

For the FCM case shown in Figure 3, the bulk density of the initial body was 2,500 kg/m$^3$, with a diameter of 1.388 to reproduce the assumed 3,500 kg mass estimate used to derive the Košice energy deposition. The material density of all rubble pieces was set to 3,400, based on the mean density of discovered meteorite falls from the event [Gritsevich et al., 2014; Tóth et al., 2015]. However, similar matches could also be obtained using bulk densities ranging from 1,100–3,400 kg/m$^3$ if the diameter was varied (1.825-1.253 m) to maintain roughly the same mass. The initial body was disrupted near the beginning of the light curve, at around 1.8–2 kPa of stagnation pressure, and was separated into four structural groups to reproduce the two primary flares and the overall slope and minor flares along the rest of the profile. No debris was released with initial rubble disruption.

The large lower flare at around 37 km altitude was best modeled using one primary fragment comprising around 80% of the initial mass. This rubble fragment began breakup at around 1.15 MPa of stagnation pressure, with a strength-scaling exponent ($\alpha$) of 0.3 and a moderate cloud mass fraction of 50%. The smaller upper flare near 53 km altitude was best matched using two different rubble fragments, each with ~2–4% of the initial mass (totaling 4–6% combined), with one beginning fragmentation between 35–40 kPa and the other slightly lower at 55–70 kPa of stagnation pressure. The slightly weaker one, modeled with a moderately low strength-scaling $\alpha$ (0.1), was needed to match the rapid fragmentation along the top of the flare, while the slightly stronger one, modeled with a high strength-scaling $\alpha$ (0.6–0.8) was needed to better match the broader nose of the flare and contribute to the small sub-flares below. For both main flares, the best matches were obtained using moderate cloud mass fractions of 40–60% (50% used for case shown), and fairly uneven fragment mass splits of around 80/20%.

In addition to these three large primary fragments, early disruption of many very small fragments was needed to match the energy deposition levels along the upper slope of the profile. The undisrupted body (or disruption with only a few main fragments) yielded energy deposition values a factor of 5–6 smaller than the nominal observational estimates. The best matches to the upper slope of the profile were obtained using of a group of several hundred (300–600) rubble pieces, totaling 14–16% of the initial mass. To reproduce the minor high-altitude flares, these pieces began fragmentation at the top of the observed profile, with a very low fragmentation rate (using a very high strength-scaling $\alpha$ of 2), a very low cloud mass fraction of 0.2%, and the same uneven mass splits. Releases of these tiny, rapidly dispersing cloud masses was the only way to produce such small, sharp features at these high altitudes within FCM. However, the constant ablation coefficient used in the current model and the constant luminous efficiency assumption
used to derive energy deposition from the light curve data may limit any specific mass or ablation inferences from these high-altitude features. The form of these small flares may also be influenced by smoothing on the observed light curve, which was observed at 500 Hz on a radiometer, and smoothed over 10 consecutive measurements [Borovička et al., 2013a]. Similarly, FCM results are integrated at 10-m altitude steps but are averaged to 1-km resolution for these comparisons.

In terms of modeling parameters, the case shown used the nominal $1 \times 10^{-8}$ kg/J ablation coefficient, and a reduced cloud dispersion coefficient of 2. However, the Košice matches were not as notably or consistently influenced by these parameters as the more cloud-driven Chelyabinsk case, and reasonable matches could also be obtained using the baseline spread rate, or lower ablation coefficient values. Borovička et al. (2013a) used an ablation coefficient of $5 \times 10^{-9}$ kg/J ($0.005 \text{ s}^2 \text{ km}^{-2}$) in their primary modeling of Košice, but noted a broad potential range of $1 \times 10^{-9}$ to $1.5 \times 10^{-8}$ kg/J given uncertainties in mass and luminous efficiency assumptions.

For comparison with results from another modeling approach, Borovička at al. (2013a) presented a detailed fragmentation history from their modeling of the Košice breakup. Their model prescribed 11 specific breakpoints along the trajectory, where specified portions of the mass were set to separate as individual fragments, groups of fragments, eroding fragments, or dust. Those results had a smaller fraction of the initial mass going into the main flare compared to our results (57% vs. 80%). For the upper flare, their model divided the event into two main fragmentation events between 57–55 km altitude, similar to our use of two different rubble pieces in that region. A higher fraction of the initial mass (43%) was separated from the meteoroid during those two phases in their model, compared to the 20% combined mass fraction of the three rubble groups that broke up above 55 km in our model. The Borovička model did not include any fragmentation above the flare at 57 km, but it did use 200 grouped small fragments (5-10 kg each) to form the profile slope between the upper and lower flare, similar to the 300 small fragments (1.6 kg each) that our model released at 75 km altitude to reproduce the energy deposition levels above and below the first flare. Interpretations of the differences between the two modeling results are somewhat difficult due to the many different types of fragmentation schemes included in the Borovička model, compared to our simpler, more generalized fragmentation approach.

4.3 Benešov

Figure 4 shows an FCM energy deposition match obtained for the Benešov meteoroid, which was estimated have an initial mass of 4,100 kg, entry velocity of 21 km/s, and steep entry angle of 81° from horizontal [Ceplecha & ReVelle, 2005; Borovička et al., 1998].
Figure 4. An FCM energy deposition match for the Beneš meteoroid, using 15 individual structural fragments. The plot on the left shows the FCM energy deposition results compared with estimates derived from the observed light curved, assuming an initial mass of 4,100 kg for the nominal solid line and a factor-of-two range (2,050–8,200 kg) for the dashed uncertainty bounds [Borovička et al., 1998; Ceplecha & ReVelle, 2005]. The plot on the right shows a breakdown of the rubble fragments used for this match, with dots representing each individual rubble, sized by relative diameter and colored by relative mass. The identical rubbles in each group are aligned at the altitude where they begin breakup, with the corresponding breakup strength/pressure shown along the right axis. The horizontal axis shows the mass of each rubble. This match used single individual rubble pieces rather than groups of identical rubbles.

An energy deposition curve for the Beneš meteor was computed using the same method as for the Košice meteor. In this case, the light curves given by Borovička et al. (1998) and Ceplecha & ReVelle (2005) were used to compute the meteor radiated power, again assuming that a zero-magnitude meteor radiated 1,530 W. The total light output of the meteor, 0.014 kt, and the initial kinetic energy, 0.22 kt, yielded an integrated luminous efficiency of 6.1%, exceeding the predicted range of 0.05–2.05% given by Ceplecha & ReVelle (2005). The energy deposition curve in Figure 4 was computed by dividing the radiated power by the luminous efficiency.

Ceplecha & ReVelle (2005) estimated that the initial mass of 4,100 ± 100 kg for the Beneš meteoroid based on their model. Borovička et al. (1998) estimated an initial mass of 3,000–4,000 kg using a progressive fragmentation model, but also estimated a mass between 2,000 and 8,000 kg using a separate model that did not reproduce the meteoroid speed and dynamics as precisely. In Figure 4, the energy deposition corresponding to an initial mass of 4,100 kg is given as the nominal solid curve, while the dashed curves give bounds for initial masses within a factor of two (2,050–8,200 kg). There were no independent measurements of the initial kinetic energy for comparison.

Cases were modeled using densities from 2,000–3,700 kg/m³, following the alternate ranges used in Borovička et al (1998), with the diameter adjusted to maintain the 4,100 kg mass estimate adopted for the observational energy deposition curve. Scaling the size/density combination in this way did not noticeably change the energy deposition results, and so these properties cannot
be uniquely inferred from these comparisons. However, the initial rubble mass fractions and fragmentation parameters used to match the form of the profile were also insensitive to the particular choice of size/density and remained similar across the range of cases modeled in this study. The case shown in Figure 4 used a density of 3,200 kg/m³, based on the LL3.5 and H5 typing of meteorite finds reported by Spurný et al. (2014) and the mean bulk densities of LL and H type falls (3,180 and 3,350 kg/m³ respectively) [Flynn et al., 2017; Macke, 2010].

Reproducing the gradual humped slope of the upper profile required many very small fragments beginning breakup at different points along the descent. Initial structural disruption occurred at around 65-67 km and 20-25 kPa of pressure. The best matches were obtained using 8 or more small initial fragments, each with masses between 0.05–0.2% of the initial asteroid mass (~1% total), beginning breakup along the profile’s upper hump at stagnation pressures between 25 kPa and 1 MPa, followed by a few slightly larger fragments (1–7% each, totaling ~10% initial mass) breaking up along the top of the peak, at 1–2 MPa.

The three larger spikes along the nose of the main flare were matched using structural fragments of around 30–35%, 15–20%, and ~35% of the initial mass, beginning fragmentation at around 2.9, 3.8, and 17 MPa of stagnation pressure, respectively. Reasonable matches could also be obtained by dividing each of these large pieces into 2–6 smaller identical constituents, reducing the mass fraction of the largest pieces to 6–17%. However, further subdividing the masses tended to steepen the profile between the upper hump and the main flares (due to the increased drag from more separated fragments), and tended to narrow and sharpen the main flares (due to the fragmentation debris being deposited in smaller subdivided increments).

For comparison, the Borovička (2015) dynamical assessment of Benešov wake length and deceleration determined that initial disruption started at 70 km altitude and 50 kPa, with a resulting fragment mass range of 0.1–40 kg and the largest fragment comprising only 1–2% of the initial mass. That assessment also associated the primary flares with lower dynamic pressures of 2.5–9 MPa, presumably because it accounted for the greater observed deceleration along the entry. Our current FCM modeling is based only on the energy deposition derived from the light curve and is not adjusted for observed dynamics beyond the initial velocity and angle. These pressure and fragment mass differences suggests that improving FCM’s simplified representation of separated fragments may be warranted for better assessment of cases like Benešov, where there is strong deceleration and the photometric and dynamic mass estimates diverge. However, our results do agree in the general finding that the bolide disrupted into many smaller fragments above 65-70 km altitude, and exhibited gradual breakup over the course of the upper profile.

In our FCM cases, moderate cloud mass fractions of around 50% produced the best matches for most of the fractured structural components. The final, sharp flare, however, was best matched using complete breakup into a single large debris cloud that dispersed its energy rapidly in the denser, low-altitude atmosphere. The case shown used 2 fragments per break, with uneven mass splits of 80/20% and strength-scaling exponents ranging from 0.4 for the higher fragmentations, to 0.2 for the lower fragmentations. Like the Košice case, this case also used a reduced cloud dispersion coefficient value of 2 and nominal ablation coefficient value, but was not notably dependent on these parameters.
Given the 4,100 kg mass estimate employed, the Benešov profile proved difficult to reproduce in the very low-energy-deposition regions at the very beginning of the entry and below the final flare. Modeling factors likely contributing to the differences include the use of a constant ablation coefficient in the FCM modeling and the constant luminous efficiency assumption used to estimate energy deposition from the light curve. According to Ceplecha & ReVelle (2005), the luminous efficiency vanishes at low altitudes due the fragments being largely decelerated, and at high altitudes since the atmosphere is rarefied. As a result, the constant luminous efficiency assumption may underestimate the true energy deposition in the high and low altitude regimes. However, while readily apparent on log-scale plots, these differences are fairly small (under $1\times10^{-6}$ kt/km).

### 4.4 Tagish Lake

Figure 5 shows an FCM energy deposition match obtained for the Tagish Lake meteoroid, which was estimated have an initial mass range of $5\times10^4$ to $1.8\times10^5$ kg, an entry velocity of 15.8 km/s, and a shallow entry angle of around 18° [Brown et al., 2002]. We modeled the Tagish Lake breakup using these entry parameters along with a bulk density of 1,640 kg/m$^3$ based on the mean density of meteorite finds [Hildebrand et al., 2006].

![Figure 5](image_url) An FCM energy deposition match for the Tagish Lake meteoroid, using 15 structural groups. The plot on the left shows the FCM energy deposition results compared with estimates derived from the observed light curved, assuming 16% luminous efficiency for the nominal solid line, and 5–20% luminous efficiency range for the dashed uncertainty bounds [Brown et al., 2002]. The plot on the right shows a breakdown of the structural groups used for this match, with dots representing each individual rubble, sized by relative diameter and colored by relative mass. The identical rubbles in each group are aligned at the altitude where they begin breakup, with the corresponding breakup strength/pressure shown along the right axis. The horizontal axis shows the cumulative mass of the rubbles for each group, such that the first (leftmost) dot gives the individual mass of each identical rubble piece, and the last (rightmost) dot gives the total mass of the combined rubble group (though some groups contain only one single rubble piece).
We generated an energy deposition profile for the Tagish Lake meteor using the observed light curve data and luminous efficiency estimates published in Brown et al. (2002). The Brown et al. analysis estimated an integral luminous efficiency range of 5–20%, corresponding to an initial mass range of $5 \times 10^4$ – $1.8 \times 10^5$ kg, and determined 16% luminous efficiency and $5.6 \times 10^4$ kg initial mass to be the most likely. Accordingly, the nominal energy deposition curve shown in Figure 5 was generated assuming a constant 16% luminous efficiency, with the lower and upper bounds respectively generated assuming constant 20% and 5% luminous efficiencies.

The Tagish Lake meteor exhibited an unusual combination of light curve features and meteorite properties, and provided an interesting test case for exploring the variability and limitations of current fragmentation modeling approaches. The high-altitude cascade of minor flares throughout the upper entry profile followed by 2–3 distinct catastrophic flares at much lower altitudes could not be effectively modeled using previous uniform structural assumptions and uniform breakup approaches. Using the current FCM rubble pile framework to match these disparate features underscored some of their key differences.

Firstly, across all the FCM fits obtained in this study, we found that the nominal $5.6 \times 10^4$ kg initial mass estimate did not provide enough energy to fill out the entire profile, tending to underpredict magnitudes along the upper portion of the profile and/or fall short in the width of the primary flares. Instead, better matches were obtained by increasing the assumed initial mass to $7.8 \times 10^4$ kg, with a diameter of 4.5 m for the bulk density of 1,640 kg/m$^3$ adopted from Hildebrand et al. (2006). However, the use of a constant ablation coefficient in the model and the constant luminous efficiency assumed in the observational energy deposition estimate again both leave notable uncertainty in the energy deposition magnitudes, particularly in the high-altitude regimes.

In reproducing the two primary flares (at around 32 and 36 km altitude), both required sudden, catastrophic fragmentation of distinct portions of the mass into small debris. The increasing size of the flares (i.e., with the largest flare at the lowest altitude) meant they could not be represented by successive fragmentation with Weibull-like strength scaling. Rather, each had to be treated as the onset of a distinct fragmentation event. The final flare (32 km altitude) was best matched using around 48–50% of the initial mass disrupting catastrophically into debris at pressures between 2.5–3.6 MPa. The preceding flare at 36 km altitude was best matched using around 38% of the initial mass, disrupting between around 0.9–1.9 MPa. Both of these flares required very large cloud mass fractions, with 98-100% of the fragmenting mass released as debris clouds. The match shown in Figure 5 used debris mass fractions of 99% for the first main flare at 36 km, and 100% cloud mass fractions for the final large flare.

In the case shown in Figure 5, the width and shape of each main flare was also more specifically matched by further dividing its fragmentation into 3 structural groups, disrupting at slightly different attitudes/pressures within the width of the peak. Although they each appear to be relatively simple, uniform flares, their particular shape and width were not readily reproduced by uniformly applying nominal single-body debris cloud parameters or progressive fragmentation parameters to a single initial mass. Attempting to model each flare as a single debris cloud mass at these low altitudes produced overly narrow flares, even when significantly reducing the cloud dispersion coefficient. The cloud dispersion coefficient had to be reduced to 0.1 (from the
nominal value of 3.5) to roughly match the width of these flares at these altitudes and material density assumptions. However, reducing the dispersion rate that much compromised the ability to match the small, higher-altitude features, and so an intermediate dispersion coefficient of 1 was used for the case shown in Figure 5.

These two lower flares were also very sensitive to the progressive fragmentation of any remaining independent fragments not treated as debris. Any such fragments needed to undergo very rapid breakup—employing very low strength-scaling exponents of under 0.05—in order to keep any successive fragmentations within the width of the observed flares. Attempting to broaden the width of these peaks by increasing the strength scaling exponent or introducing more uneven fragment mass splits tended to either produce additional sub-flares or excessive fragment masses persisting below the end of the observed breakup (generally without significantly improving the width of the main peak).

Moving up the profile, the small flare seen at around 47 km altitude was modeled using around 4.6% of the initial entry mass breaking up at around 0.14 MPa, using cloud mass fraction of 80% and a strength-scaling exponent of 0.3. Breakup of another 2–3% of the initial mass contributed to the energy deposition levels between this flare and the primary flares (between 45–40 km altitude).

Reproducing the series of small but distinct flares throughout the upper portion of the entry (75–50 km altitude) required the progressive breakup of many very small fragments, producing flashes through the release of many very small debris clouds. With the current FCM structural framework, this could be effected either using a handful of initial small rubble pieces that each disintegrate quickly into many small sub-fragments, or by releasing swarms of several hundred fragments upon the initial disruption of the body. In either case, a total of around 4.5–7% of the initial entry mass underwent breakup at dynamic pressures of 1–90 kPa, with around 0.5–1.2% of the initial mass contributing to each 3- to 5-km-wide mini-flare. The match shown in Figure 5 used the first approach with a moderately low strength scaling exponent of 0.1, two fragments per split, and a low cloud mass fraction of 20%. Although we did not pursue attempts to align the specific flare altitudes or spacing using the second approach, it could produce a similar cadence of small flares. In these cases, the mass was divided into groups of 50–1,000 initial rubble fragments, with their progressive breakup spread more sporadically across the altitude range using uneven fragment mass splits and a higher strength scaling parameter of around 0.5. The intention of these observations is not to make unique inferences about the specific fragmentations splits at given altitudes, but rather to reflect the range of modeling approaches and parameter values that can reproduce these types of unusual high-altitude features. Regardless of the specific rubble fragment distributions, all reasonable matches obtained relied upon a compilation of very small, rapidly dispersing debris clouds released from small fragmentations with low cloud mass fractions of 10–30%.

The distributions of rubble masses fragmenting at various altitudes in our results are in reasonably good agreement with the FM fragmentation model mass loss results that Ceplecha (2007) presented for Tagish Lake. Converting the incremental mass loss percentages from Table 2 of that paper into percentages of the total initial mass for comparison with our results above, the FM solution had around 5% of the mass fragmenting in increments of 0.08–0.75% across the
upper portion of the entry profile above 50 km altitude, around 4–5% of the initial mass fragmenting between 50–46 km altitude in the region of the first minor flare, around 30% fragmenting at 40–38 km in the region of the first main flare, and around 50–55% of the initial mass fragmenting in the final flare from 35–30 km altitude.

The FCM energy deposition fits we obtained for Tagish Lake also produced landed fragment masses within the range of estimates from discovered meteorite falls and other models. FCM modeling of Tagish Lake produced total fallen fragment masses of between 100-1,000 kg, with individual terminal fragments masses ranging from hundredths of a gram to several kg. The case shown in Figure 5 yielded a total landed mass of 190 kg, with 180 kg of meteorites over 0.1 g, 170 kg of meteorites over 1 g, and a maximum meteorite mass of 2 kg. In comparison, Hildebrand et al. (2006) gave the total mass of all recorded fragments to be 16.3 kg, with the largest discovered fragment around 2 kg. They also estimated around 60 kg of landed mass based on the areal fall density of meteorite finds, and estimated at least 800 kg of gram-sized or larger falls based on extrapolation of cumulative number-mass distribution of finds. The entry modeling in Brown et al. (2002) estimated 1,300 kg of gram-size or larger meteorites from Tagish Lake. These comparisons were helpful in better constraining the range of initial structures and fragmentation parameters that provided the best fits.

It is also interesting to consider the very low strengths of the Tagish Lake meteorites [Hildebrand et al., 2006; Brown et al., 2002] in relation to the entry and breakup modeling. Although one may intuitively assume that fragments surviving to the ground represent the strongest portions of material that would have fragmented last, the dynamic pressures at which the lower flares occurred (between roughly 1–3.5 MPa) seems to be at odds with the weakness of the meteorites. However, our modeling found the two final flares to be best represented by catastrophic disruption almost entirely into debris clouds, while the higher altitude flares involved more gradual discrete fragmentations at low pressures. Many of the sub-kilogram fragments persisting to the ground originated from the earlier breakups in our model. This may suggest that the weak meteorite finds could have been shed at higher altitudes, and survived to the ground after being decelerated or shielded in the wake of a larger leading body.

5. Conclusions

These cases demonstrate the range of breakup characteristics that asteroids of different sizes and structures can exhibit, and provide insight into what modeling approaches or parameters provide good approximations of the resulting energy deposition.

The large, relatively uniform flares of the Chelyabinsk meteor were well matched using predominantly debris-cloud-driven modeling. This included an initial early release of loose debris at the beginning of the disruption, and a high fraction of the mass released as debris with each successive fragmentation. These types of flares may be associated with a more heavily fractured or rubble pile structure, with a notable amount of small debris and/or material that disintegrates more readily into small debris.

The smaller meter-scale Košice and Benešov meteoroids, on the other hand, were more notably driven by their specific fragment characteristics than by large releases of debris. For both cases,
the upper profiles were not well matched by release of a debris cloud with the initial rubble disruption. Instead, many very small fragmentations spread throughout the altitude range were needed. This may be more indicative of material sluffing off the surface of a more coherent pre-fractured body than of fragments and small particulates released all at once from disruption of a loose rubble pile. Similarly, the subsequent successive fragmentations were best matched using lower cloud mass fractions than the Chelyabinsk case, potentially indicating compositions or materials that break more cleanly along fractures rather than crumbling readily into puffs of debris. These cases may support the intuition that smaller meteoroids tend to have a more coherent structure than larger bolides, but more observational comparisons would be needed to assess this trend. Additionally, more accurate treatments of variable ablation coefficients, luminous efficiencies, and fragment separation are needed to improve inferences for these high-altitude features.

Tagish Lake provided an interesting intermediate case, exhibiting a gamut of different fragmentation characteristics between its small high-altitude flares and two large primary flares. The series of progressive fragmentations and small debris masses needed to reproduce the high-altitude flares may be representative of a steady material sloughing, similar to the Benešov and Košice cases but with a much greater fraction of very small debris breaking away at the higher altitudes. In contrast, the lower flares were best represented by catastrophic breakup into large debris clouds. The overall trends in modeling the range of Tagish Lake energy deposition features were that the lower altitude flares involved increasingly larger, sudden releases of debris with less discrete progressive fragmentation behavior, while the higher altitude features required increasingly greater numbers of smaller and smaller fragments that released only a small fraction of debris as they underwent more gradual, low-pressure separation. This trend of the lower altitude flares resulting in rapid pulverization versus more gentle, discrete fragmentation at high-altitudes may support the possibility that the weaker meteorite finds were shed at higher altitudes and lower pressures rather than originating from the final flares.

For all four meteor cases modeled, reducing the cloud dispersion coefficient and/or ablation coefficient from their nominal values also provided improved matches. These effects were more notable for the cloud-driven flares in the Chelyabinsk and Tagish Lake cases than they were for the Košice and Benešov cases, which could also be matched reasonably well with the baseline parameter values. For Tagish Lake, dispersion coefficients as low as 0.01 were needed in order to reproduce the width of the two primary flares as single debris clouds, while more rapid cloud dispersion was needed to achieve the distinct small flares at high altitudes. An intermediate dispersion coefficient value of 1 provided reasonable fits for both regimes, with more rapid debris dispersal at high altitudes accomplished by using very small debris clouds, and broadening of the lower peaks accomplished using multiple large bursts of debris. These differences suggest that the current simple dispersion formula [Hills & Goda, 1993] may not scale well over a large range of altitudes and debris masses, or that the debris material released high up had a much lower effective density than the debris material released in the primary flares. Further examination and refinement of debris spread rates would benefit modeling of large flares like Chelyabinsk, while variable ablation rates and luminous efficiencies that account for altitude, size, and velocity may be needed to better match fainter features above and below smaller flares. The need for reduced ablation coefficient values is similar to the trend that Ceplecha & ReVelle (2005) noted between their intrinsic coefficient values, which explicitly account for
fragmentation effects, and apparent values based on single-body models. Recent aerothermodynamic simulations have also found significantly lower heat transfer coefficient values (translating to lower ablation coefficient values) when coupled radiation and ablation are included [Johnston et al., 2018 forthcoming].

Ongoing FCM development includes incorporating variable ablation rates and developing improved models for fragment separation, debris shedding, and debris spread rates. We have begun to incorporate size-, altitude-, and velocity-dependent heat transfer coefficient values based on the Johnston et al. (2018, forthcoming) simulation results, and an initial comparison of FCM results using these values for a Tunguska-scale case is presented in that paper. Additional work is also in progress to compute luminous power output from FCM results directly, rather than estimating energy deposition from the meteor light curves. This will enable more direct light curve comparisons without requiring initial knowledge of the mass range, and will enable variable luminous efficiencies to be accounted for within the modeling. A third area of ongoing work is the development of automated FCM light curve/energy deposition curve matching, using objective functions to evaluate the fit of the results to the observed curve along with a genetic algorithm approach to evolve the selection of input parameters according to the best fits. This work will enable efficient analysis of more observed light curves, along with more exhaustive exploration of the parameter space within observational uncertainty bounds, objective comparison of the resulting fits, and assessment of the relative likelihood or uniqueness of the parameter ranges among various fits.

Acknowledgements

This work was funded by NASA’s Planetary Defense Coordination Office. P. Brown and E. Stokan were supported by the NASA Meteoroid Environment Office through co-operative agreement NNX15AC94A.

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