IAA-PDC-15-05-04
SENSITIVITY OF GROUND DAMAGE PREDICTIONS TO METEOROID BREAKUP MODELING ASSUMPTIONS

Donovan L. Mathias(1), **Darrel K. Robertson**(2), **and Michael J. Aftosmis**(3)
(1) *NASA Ames Research Center, M/S 258-5, Moffett Field, CA, 94305,*

(2) *Science and Technology Corporation, NASA Ames Research Center, M/S 258-6, Moffett Field, CA, 94305,*
(3) *NASA Ames Research Center, M/S 258-5, Moffett Field, CA, 94305,*

Keywords: *meteoroid breakup, airburst, ground damage, blast wave, physics-based modeling*

Extended Abstract—

Meteoroid breakup, and the resulting energy deposition, has been widely studied and a number of analytical models have been presented (Refs. 1, 2, 3, 4). These models typically provide good qualitative descriptions of the energy deposition process, but are necessarily limited by simplifying assumptions. As a consequence, their results vary significantly depending on the specific modeling assumptions, and this variation translates into wide uncertainty in the resulting ground damage predictions. In this paper, meteoroid breakup simulations were performed using the ALE3D hydrocode (Ref. 5), and the effects of modeling assumptions on computed energy deposition curves are considered. In addition, the methods used to convert the energy deposition into a shock wave and propagate the shock to the ground are investigated using the Cart3D flow solver (Ref. 6).

The motivation for the ground damage modeling assumption study arose from the initial results of a physics-based impact risk model (Ref. 7), which is being developed to estimate casualties from various asteroid impact scenarios. Currently, the results are being used to show the sensitivity of the casualty estimates to uncertainties in impactor characteristics and entry conditions. These sensitivities are used to prioritize other aspects of a broader planetary defense endeavor at NASA Ames Research Center (Ref. 8). To ensure that the sensitivity results are producing proper trends, the modeling assumptions used in the risk model must also be assessed. The current paper is one element of this effort. The initial focus is on a "Chelyabinsk-like" object with a 20-m diameter and an entry speed of 20 km/s.

The computed results from this investigation show that the notion of a single breakup altitude is overly simplistic, as meteoroid breakup appears to be a more continuous process. Structural failure does follow the "pancaking" theory in certain cases, as shown in Figure 1, but the rate of radius increase is computationally lower than predicted by the analytical models (Ref. 1). In addition, pressures that exceed the material strength locally do not necessarily trigger a complete breakup, resulting in a more gradual energy deposition rate, as shown in Figure 2.

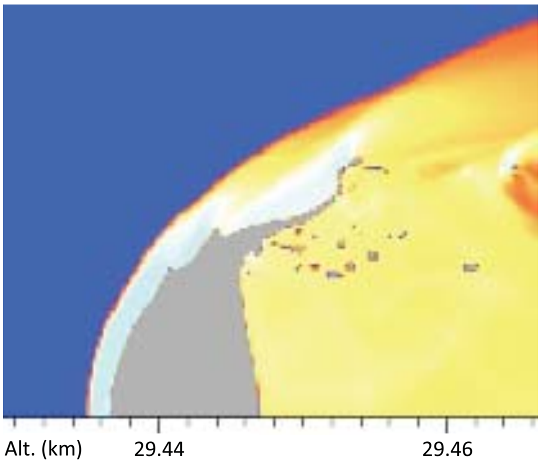

Figure 1: Deformation of the meteoroid solid (gray) due to aerodynamic entry loads. The field is colored by velocity magnitude. Diameter = 20 m, velocity = 20 km/s, density = 3.1 g/cc, entry angle = 90 deg.

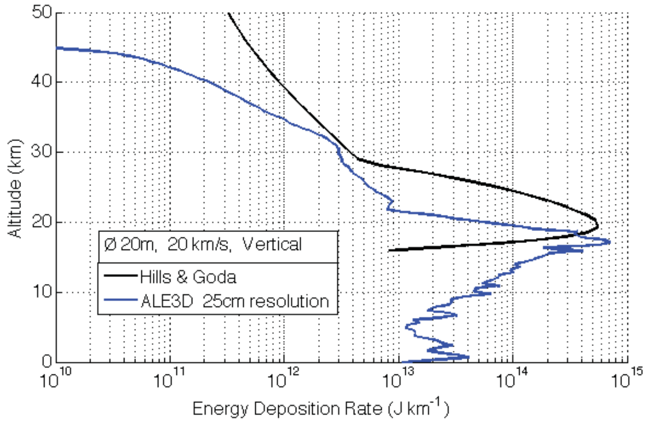

Figure 2: Energy deposition rate from simulation shown in Fig. 1, compared with analytical model from Ref. 1.

The current computations also do not exhibit a discrete fragmentation behavior over the range of material models investigated. Figure 3 shows solutions for objects with and without strength under the same entry conditions. The presence of material strength does reduce the deformation, as shown, but the energy deposition curve is not drastically changed.

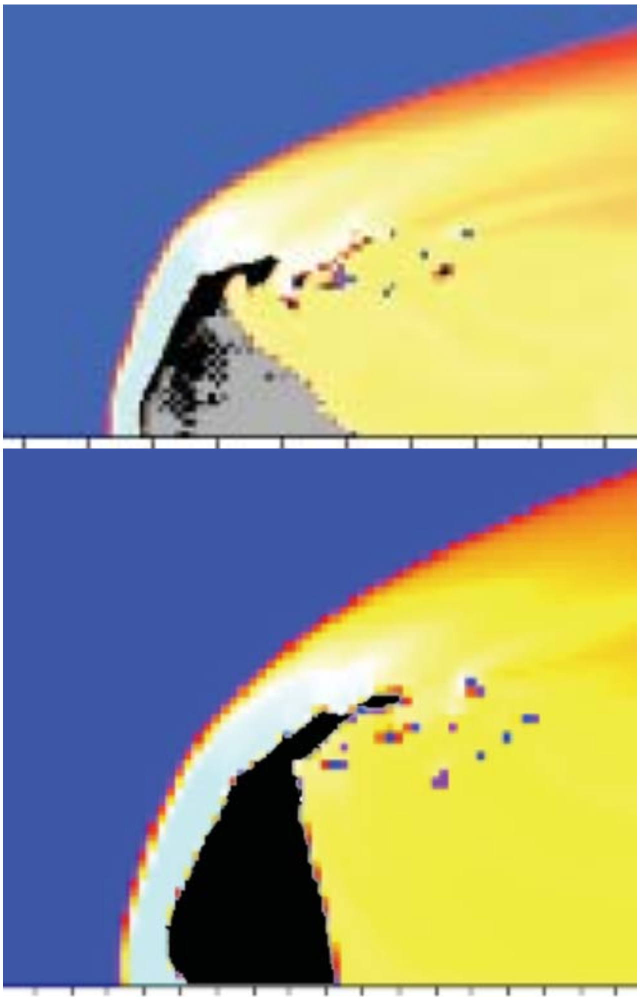

Figure 3: Deformation comparison for 20 km/s vertical entry. The upper frame shows an object with strength of 10 MPa and the lower frame shows an object with no strength. Diameter = 20 m, velocity = 20 km/s, density = 3.1 g/cc, entry angle = 90 deg.

Using material strength as a means of differentiating breakup altitude is potentially informative, but by itself omits other important issues (Ref. 9). For example, Figure 4 considers two simple geometries under representative aerodynamic entry loads. Both cases are assessed using ALE3D with the same material model, but fail in very distinct ways. These results, while intuitive in this case, highlight that discrete fragmentation, and associated energy deposition, can depend as much on geometry as the details of internal structure and strength.

The kinetic energies of the meteoroid fragments are integrated over time to produce energy deposition curves. These curves provide initial conditions for blast propagation simulations performed using Cart3D, a Cartesian Eulerian flow solver (Ref. 6). The resulting flow solutions are then used to produce the ground damage footprints associated with the airburst. Typically, ground damage is estimated using a spherical charge (Ref. 10) or as a line source (Ref. 11).[1]

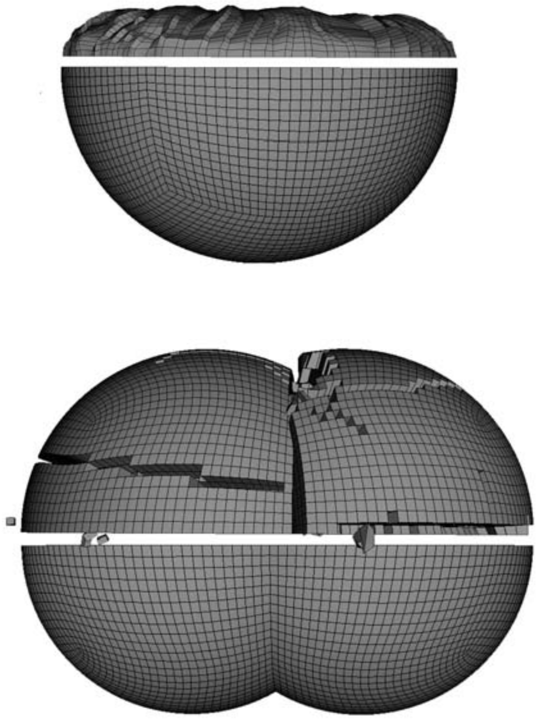

Figure 4: Comparison of spherical and merged-sphere geometries under similar load conditions. Results from Ale3D simulations using Lagrangian elements and the same material model. Top half of each image represents the “failed” geometry while the bottom shows the initial configuration.

Since the spherical source is much simpler to use in a general model, the two approaches are compared. Figure 5 shows Mach contours arising from a line source compared to those from a spherical source. The total energy added is the same for both cases, and the point source is initiated at the altitude of the line source’s peak energy deposition. As seen, the near-field flows are quite different, but by the time the shock waves reach the ground, the patterns are visually similar. Directly under the burst, the sphere produces higher peak overpressures, but the two converge as the shock propagates away from ground zero.

---

[1] Other researchers (Ref. 12) have performed assessments in which energy is added to the flow simulation around an entering object and the resulting blast propagation manifests. This approach has been recreated by the authors, but is not included here because an “airburst altitude” must be prescribed. The current paper focuses on approximations associated with the coupled modeling of the energy deposition and the blast propagation.

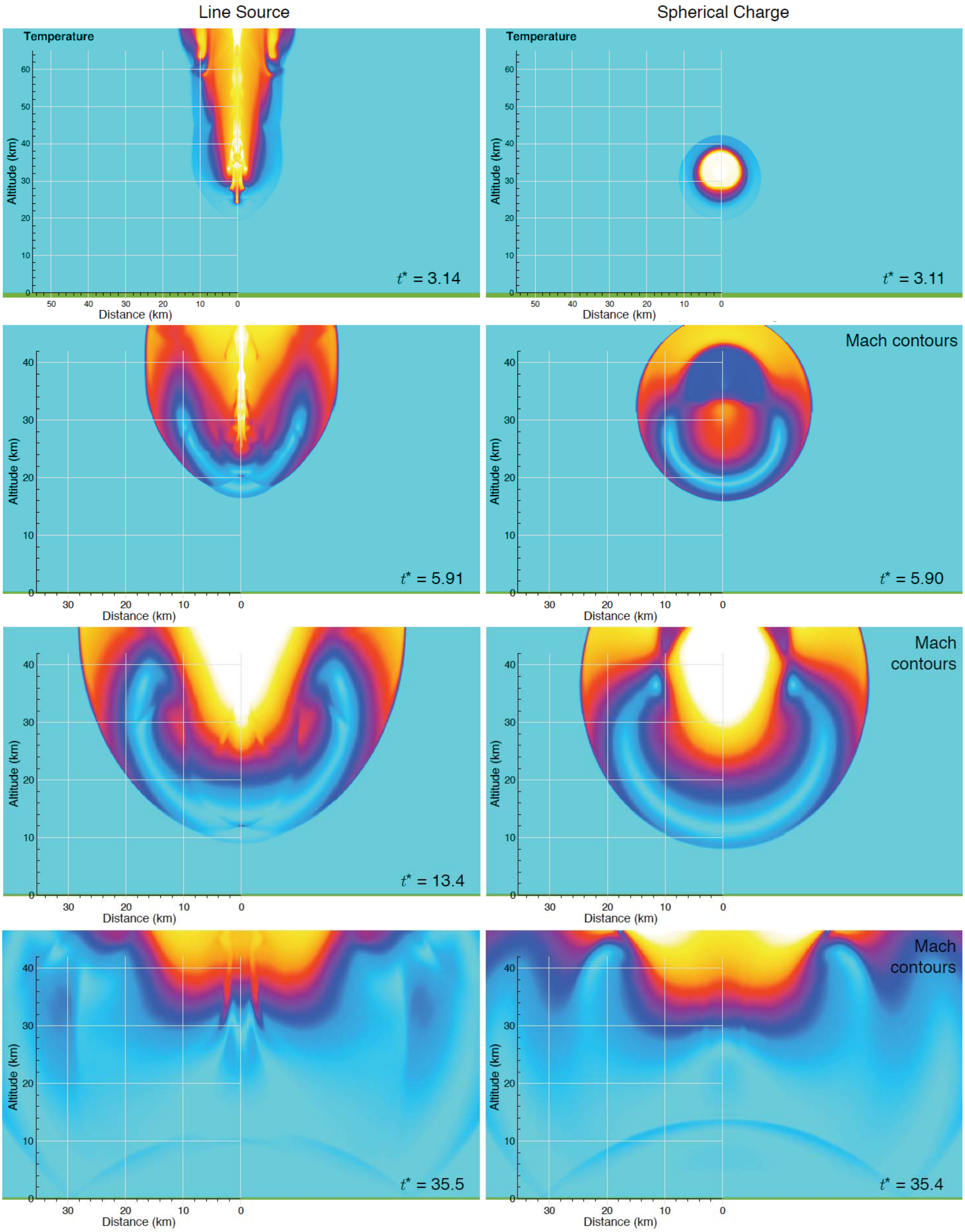

Figure 5: Mach contours for linear energy deposition (left) and spherical source (right) at four propagation times. Energy is derived from a 20-m object at 20 km/s.

A similar comparison was performed for an entry angle of 18 degrees, and the results are shown in Figure 6. The resulting ground footprints are topologically different, and the area enclosed by a contour level varies by magnitude. At 2% overpressure, the areas appear to match quite well, but at 6%, the area difference has become large. The appropriateness of each method depends on the application; if the airburst is near the ground, or if the specific details of the footprint shape are important, then the distributed source should be used. However, in cases where the results are measured in terms of an average damage area and the burst occurs at altitude, then the spherical source provides a reasonable approximation.

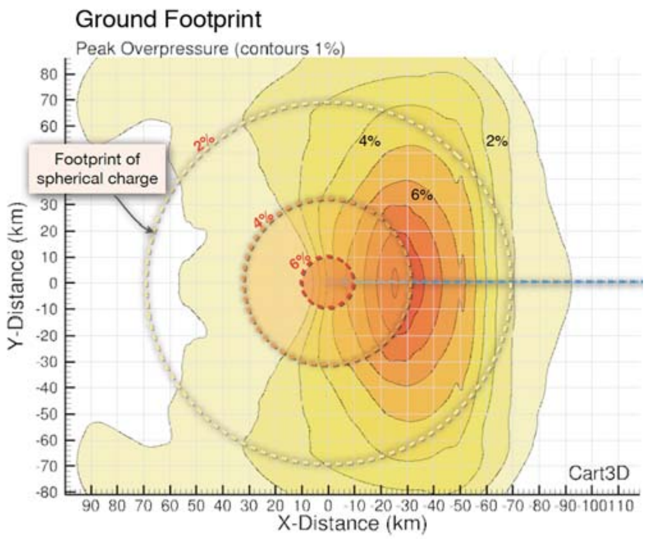

Figure 6: Peak overpressure footprint for the case shown in Fig. 5, but at 18 deg. entry. Color contours represent the line-source energy deposition and the dashed circles are due to a spherical source.

A breakup simulation was performed for an impact of the hypothetical 2015 PDC asteroid (Ref. 13), and results are shown in Figure 7. Due to the large size (100–500 m, modeled as 150 m), very little of the energy is deposited in the atmosphere prior to ground impact. Therefore, there is not an airburst per se, and the resulting blast energy would require an impact simulation that is outside of the scope of the current work.

The broader results of this study have identified areas where simplifying assumptions are reasonably representative when performing risk sensitivity studies. At the same time, there are some modeling assumptions that clearly require additional fidelity for more detailed assessments. Results also show that next steps in model refinement should focus as much, or more, on shape bounding than on modeling details of strength and material failure.

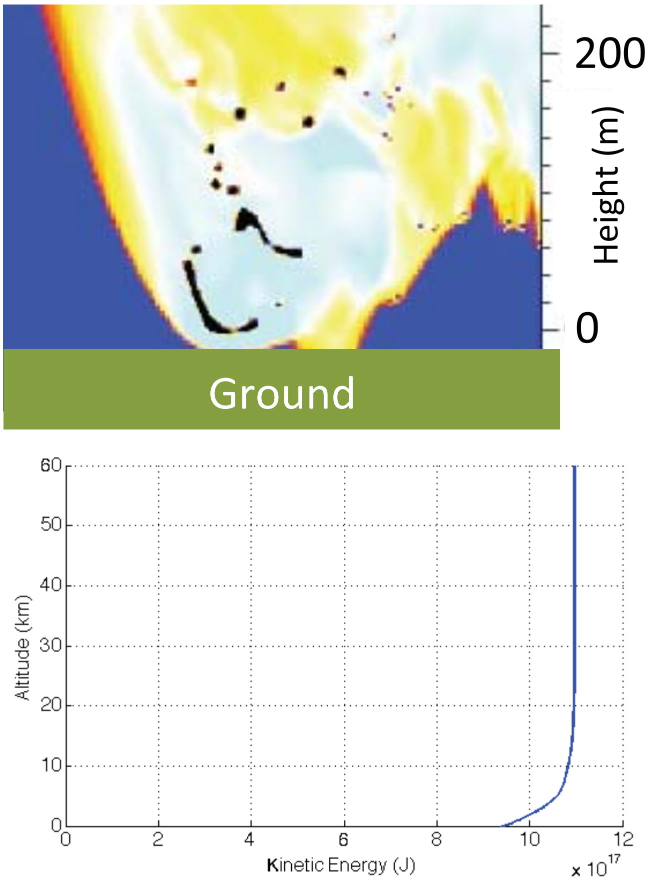

Figure 7: Impact simulation results for a 150-m diameter asteroid, at a 20 km/s vertical entry. The upper frame shows that breakup is still ongoing as the surface is struck (vertical axis scale is approximately 200 m). The lower frame shows the kinetic energy versus altitude.

REFERENCES

[1] Hills, J. G., and Goda, M. P., *The Fragmentation of Small Asteroids in the Atmosphere,* The Astronomical Journal, Vol. 105, No. 3, pp. 1114–1144. 1993.
[2] Chyba, C.F., Thomas, P. J., and Zahnle, K. J., *The 1908 Tunguska Explosion: Atmospheric Disruption of a Stony Asteroid*, Nature 361, pp. 40–44, 1993.
[3] Grigoryan, S. S., *Motion and Breakdown of Meteorites in Planetary Atmospheres*, Cosmic Research, Vol. 17, pp. 724–740, 1979.
[4] ReVelle, D. O. and Ceplecha, Z., *Semi-empirical Fragmentation Model of Meteoroid Motion and Radiation during Atmospheric Penetration*, Proceedings of Asteroids, Comets, Meteors ACM 2002, 29 July–2 August 2002, Technical University Berlin, Berlin, Germany, ESA SP-500, ESTEC, Noordwijk, The Netherlands, B. Warmbein editor, November, 2002, pp. 285–288.
[5] https://wci.llnl.gov/simulation/computer-codes/ale3d
[6] Aftosmis, M. J., *people.nas.nasa.gov/aftosmis/**cart3d**/*
[7] Motiwala, S. A., Mathias, D. L., and Mattenberger,

C. J., *An Integrated Physics-based Risk Model for Assessing the Asteroid Threat*, Paper 12351, International Topical Meeting on Probabilistic Safety Assessment and Analysis, Sun Valley, ID, USA, April 26–30, 2015.

[8] Arnold, J. O., et al., *Overview of a New NASA Activity Focused on Planetary Defense,* Proceedings of the 4th Planetary Defense Conference, Frascati, Roma Italy April 13–17, 2015.

[9] Prabhu, D. K., et al., *Physics Based Modeling of Meteor Entry and Breakup,* Proceedings of the 4th Planetary Defense Conference, Frascati, Roma Italy April 13–17, 2015.

[10] Stokes et al., *Study to Determine the Feasibility of Extending the Search for Near-Earth Objects to Smaller Limiting Diameters*, National Aeronautics and Space Administration (2003).

[11] Popova, O. P., et al., *Chelyabisk Airburst, Damage Assessment, Meteorite Recovery, and Characterization*, Science Express, 7 November, 2013.

[12] Boslough, M. B. E. and Crawford, D. A., *Low-altitude Airbursts and the Impact Threat*, International Journal of Impact Engineering, Vol. 35, Issue 12, pp. 1441–1448, December 2008.

[13] International Academy of Astronautics, Press Release 14/5, *Hypothetical Asteroid Impact Exercise Posed for IAA Planetary Defense Conference*, December 2014. Details available at http://neo.jpl.nasa.gov/pdc15/.