VAPORIZATION DURING BOLIDE FRAGMENTATION.

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Introduction: A bolide, or fireball, is a meteor that explosively fragments during its descent through the atmosphere. There are about 35 recorded bolide occurrences annually on Earth [1]. Most of the smaller bolides are completely ablated before they reach the surface of the Earth. Some, such as the 2013 Chelyabinsk or the 1908 Tunguska super-bolides, cause significant damage during their fragmentation stage, causing an airburst that can level trees. Larger bolides may have larger fragments that impact Earth's surface, but they are significantly smaller than the original size of the meteor and some, such as the Tunguska bolide, are completely ablated in the atmosphere without any recovered fragments. It is estimated that the Chelyabinsk meteor had a diameter of approximately 18 meters before its ultimate fragmentation [2]. The largest fragment recovered from the Chelyabinsk event was less than a meter in diameter [3], meaning that less than 0.1% of the originally observed mass reached Earth's surface.

Many different numerical simulations have been done to quantify and explain the intense fragmentation and ablation that occurs during a bolide's descent, e.g. [4, 5]. This study builds on the work that Tabetah and Melosh [5] did in looking at how porosity and percolation influences and enhances the fragmentation of bolides. In this study we use the multi-material hydrocode, KFIX to show the effect that vaporization has on the fragmentation process.

Methods: KFIX, an Eulerian hydrocode developed at Los Alamos National Lab in the 1970s, is capable of modeling dual-material and dual-phase flows [6]. By modeling both the meteor material and the atmosphere as linked, continuum fluids rather than individual particles, we can effectively capture the interactions between the meteor and the atmosphere while conserving mass, energy, and momentum. If one chooses the first phase to be the atmosphere and the other to be the meteor, the exchanges of energy and momentum between the meteor and the atmosphere can be accurately modeled by KFIX [5], given suitable equations of state for the gas (we assume an ideal gas with an appropriate mean molecular weight) and solid (we use a stiffened gas equation of state [7] for basalt). For this study, we have also added vaporization and condensation, based on the work of Langmuir [8]. Instead of adding a new, third phase to KFIX, we track the mass fraction of the atmosphere that is comprised of vaporized silicates in each cell. We use this mass fraction to modify the various field equations governing KFIX's iteration scheme to correctly represent the changes the vaporized material makes to the behavior of the atmosphere.

To model a bolide, we track material in the meteor's center-of-mass frame, instead of the Earth's frame of reference. To do this we flow atmosphere in at the bottom of the computational mesh at 15 $km\ s^{-1}$, and increasing pressures according to the tracked altitude of the meteor. The mesh is axisymmetric, with the axis of symmetry running through the center of the meteor and parallel to the entry trajectory (which we have set to be 45°). Since this study focuses on the fragmentation and vaporization of the main body of the meteor and not the effects of the atmospheric shockwaves produced at further distances, this approach is sufficient.

Results: We modeled two types of bolides with a 10 m radius, one where air can permeate inside the meteor, and another where the meteor material is less permeable. To model these permeabilities in KFIX, we change the effective radius of the material making up the meteor, since the standard Darcy permeability is proportional to r^2. The non-permeable meteor has a particle radius of 5 mm, and the permeable meteor has a particle radius of 5 cm, meaning that there is a 100x difference in permeabilities between the two simulated meteors. In our simulations, we find that the non-permeable meteor has a higher rate of vaporization. A smaller effective particle radius, and thus a smaller permeability, leads to more drag acting on the bolide, which increases the friction heating of the material, which leads to higher levels of vaporization. We also find that there is a significant amount of vaporization occurring during the fragmentation of the bolide, which changes the behavior of the surviving fragments. Unfortunately, our initial results do not yet extend far enough past the fragmentation stage of the bolide's descent to track the total amount of vaporization up to when the bolide fully disintegrates, or it reaches the ground. We are working to extend our simulations to later times to determine the total mass of material vaporized during the bolide's complete trajectory. Our initial results suggest that the Tunguska meteor was finer grained and less permeable than the Chelyabinsk meteor. In future work we will explore other effects on break up and vaporization including meteor size, entry angle, and entry velocity.

References: [1] Chamberlin, A. B., (2022) *https://cneos.jpl.nasa.gov/fireballs/.* [2] Yeomans, D. K. and Chodas, P. W., (2013) *Center for NEO Studies.* [3] Kocherov, A. V. et al. (2014) *LPS XLV*, Abstract #2227. [4] Artemieva N. and Shuvalov V. V., (2001) *Journal of Geophysical Research,* 106:3297–3309. [5] Tabetah, M. E. and Melosh, H. J. (2017) *Meteoritics & Planetary Science,* 53:3:493–504. [6] Rivard, W. C. and Torrey, M. D. (1976), LA-NUREG-6623. [7] Lemons, D. S. and Lund, C. M. (1999) *American Journal of Physics,* 67:1105-1108. [8] Langmuir, I. (1913) *Physical Review*, 2:5:329-342.