ATMOSPHERIC BREAKUP OF METEOROIDS AND THE STRENGTH OF FE-NI .

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Introduction: The breakup of meteoroids in planetary atmospheres is important for understanding historic and prehistoric impacts, and for assessing the threat from future impacts. However, the observed altitudes of meteoroid breakup are not consistent with observations. The inaccuracy is such that meteoroids seem more likely to reach the surface than models predict. The discrepancy is equivalent to a factor ~10 in strength of the meteoroid material [1]. There are relatively few measurements of the strength of meteoritic material [2,3] compared with terrestrial and engineering materials, and idealized materials such as the elements; we have made new measurements on Fe-Ni meteoritic material at relatively low and high rates of deformation. There have also been suggestions that micrometeoroids might have penetrated to the ground in prehistoric impacts [4], which would not be expected based on accepted models of entry. Atmospheric flow around a meteoroid, and the stress distribution leading to deformation and breakup, are greatly simplified for rapid breakup assessments. We have made more detailed studies of the flow and response, which can be reduced to modified forms of simple breakup models.

Strength of meteoritic Fe-Ni: The strength of meteoritic Fe-Ni during dynamic loading has been investigated previously by the impact of projectiles, and found to be typically ~0.43 GPa [2]. We have previously investigated the strength of a range of Fe-Ni meteorites at lower strain rates using microindentation, and found the flow stress to be significantly larger: ~1-7 GPa. We have recently performed shock-loading experiments on samples of Diablo Canyon and Gabeon material, and again found dynamic yield stresses of ~2-3 GPa. Future studies will include measurements on precooled and preheated samples, more representative of the conditions occurring both in the bulk material and in the surface region affected by ablation. Meteoroids are heterogeneous, with spatial variations in strength, and the early stages of breakup may depend on the weakest regions of the meteoroid, but these systematically larger yield strengths may accound for much of the discrepancy in predicting breakup altitudes.

Atmospheric flow: The breakup of meteoroid during entry into an atmosphere is driven by the stress distribution induced by the flow field. For rapid breakup assessments, the stress is typically estimated as the stagnation pressure for the leading streamline, calculated in the incompressible limit [1]. However, a shock wave runs ahead of the meteoroid, modifying the peak pressure. The peak pressure and distribution around the meteoroid can be predicted by hydrodynamics simulations. The resulting stress gradient is typically several tens of percent lower than the simple estimate, accounting for the rest of the discrepancy.

Meteoroid breakup: Once the stress gradient experienced by a meteoroid is large enough to cause deformation, the breakup process is governed by the Rayleigh-Taylor instability, mitigated by the strength of the meteoritic material. Particle sizes in the breakup cascade depend on the perturbation length scales exhibiting growth. The physics of meteoroid entry is thus related closely to high-pressure strength experiments using lasers, where strength is inferred by studying the Rayleigh-Taylor growth of perturbations. Detailed simulations of the breakup cascade are inherently three-dimensional, and less tractable than simulations of the initial stress distribution, which can be represented largely in two dimensions with axial symmetry. However, a robust feature of the simulations is that, even once breakup starts, the shock cones caused by the larger and stronger fragments of the original meteoroid allow smaller fragments to be transported significantly deeper and faster into an atmosphere than would be expected by considering the interaction of the smaller particles with the atmosphere in isolation. There may therefore be instances, if the primary breakup of a meteoroid occurs deep enough within the atmosphere, for smaller fragments to reach the ground with greater speed than would be expected from their terminal ballistics in an otherwise unperturbed atmosphere. This is likely to be a rare occurrence, and in terms of assessing threat may be a small correction compared with the largest fragments, but could be included in hazard assessments.

References: [1] Collins G. et al (2005) *Meteoritics & Planet. Sci., 40,* 6, 817. [2] Furnish M. D., Boslough M. B, Gray III G. T., and Remo J. L. (1995), *Int. J. Impact Eng., 17,* 341-352. [3] Petrovic J. J. (2001) *J. Mater. Sci., 36,* 1579-1583. [4] Firestone R. B. et al. (2007) *PNAS 104*, 41, 16016.