NONLINEAR SHOCK INTERACTIONS PRODUCE HIGH-VELOCITY, LOW-PRESSURE SPALL. L. Ong[1] and H. J. Melosh[2], [1]Lunar and Planetary Laboratory, University of Arizona, Tucson, AZ 85721 (long@lpl.arizona.edu), [2]Department of Earth and Atmospheric Sciences, Purdue University, West Lafayette, IN 47907 (jmelosh@purdue.edu)

Introduction: Spallation accelerates lightly shocked ejecta fragments to speeds that can exceed the escape velocity of the parent body. These ejecta produce secondary craters or become meteorites from the Moon, Mars, and Vesta. Nonlinear shock interactions that produce spall can only be solved numerically, but hydrocode simulations to date only resolve large, low-velocity fragments.

We present high-resolution simulations of nonlinear shock interactions in the near surface. Initial results show the acceleration of near-surface material to velocities up to 1.5 times greater than the peak particle velocity in the detached shock, while experiencing little to no shock pressure.

Shock Interactions in the Near Surface: Where the shock front can be described as a planar near-discontinuity, the relationship between shock pressure P and particle velocity u_p is described by the Hugoniot equation $P = \rho_0 u_p U$ (where ρ_0 is the initial density and U is the equation-of-state dependent shock velocity).

However, in the near surface, the shock becomes irregular and can no longer be described by the Hugoniot equations. A simple analytical mechanism for the spallation of surface materials during impact describes the linear superposition of the shock with a reflected shock [1-3]. In this model, the superposition results in low pressures but high particle velocities within a geometrically derived interference zone. Because this simple model depends on linear superposition, the shock must originate at some "equivalent depth of burst" beneath the surface.

This simplistic model ignores the inherent nonlinearity of shocks. The shock and rarefaction are assumed to superpose linearly and the interference is assumed to be a function of the rise time of the incident pulse. Here we present numerical results that test the production of spall through nonlinear shock interactions in the near surface.

High-resolution simulations of Nonlinear shock Interactions in the Near Surface: We simulate near-surface shock interactions using the SALES_2 hydrocode and the Murnaghan equation of state.

Simulation setup: We model a domain in spherical geometry with a wedge-shaped grid. We do not model the area immediately surrounding the impact point to avoid the large distortion of the lagrangian mesh. At the beginning of the simulation, we impose a radial velocity pulse at the inner radius of our mesh. This radial velocity approximates the detached shock as a Gaussian stress pulse. As the shock propagates through the wedge, it interacts with the free surface and exits the domain at a continuous outflow region at the outer radius of the mesh. Test simulation results match the predictions of the simple analytical spall model for the interaction of linear elastic waves with the surface. For nonlinear shock interactions, we model the target as a solid with a nonlinear Murnaghan equation of state. We track the maximum pressure and maximum velocity attained in every cell in our simulations.

Murnaghan Equation of State: Unlike the linear elastic model, this idealized equation of state supports nonlinear shocks. It is not temperature-dependent and therefore contributes no thermal pressure. The Murnaghan equation of state describes a nonlinear pressure-density relation:

$$P = \frac{K_0}{n}\left[\left(\frac{\rho}{\rho_0}\right)^n - 1\right]$$

where K_0 is the bulk modulus and n is a constant. For this idealized model, we have chosen a bulk modulus typical for rock of 53 GPa and let n=4 (within the range of experimentally measured values for geologic materials [4]).

Results: Our simulations demonstrate that nonlinear shock interactions in the near surface produce lightly shocked high-velocity material. Unlike the simple analytical model of Melosh [1-3], spallation occurs even when the shocks originate at the surface and require no equivalent depth mechanism.

The spall is the result of the free surface boundary condition, which forces a pressure gradient from the peak shock pressure to the zero pressure boundary (Figure 1). The nonlinear shock interactions occur where the pressure contours curve to accommodate the free surface.

The material within this spall zone is ejected at speeds up to 3 km s^{-1} for an imposed pulse of 2 km s^{-1}. Where the ejection velocities are highest, the maximum pressure attained in each cell is effectively zero.
The maximum velocity is plotted as a function of maximum pressure in the cell in Fig. 2 (only a few near-surface cells are plotted for ease of viewing). For most cells in the simulation, the shock is planar and particle velocities are dictated by the Hugoniot relations (black points). However, near the surface, the velocities in the cells begin to diverge from the Hugoniot. The lowest pressures occur at the surface (red points) and increase

with depth (blue points). In these areas of lowest pressure near the surface, the particles are ejected with the highest velocities.

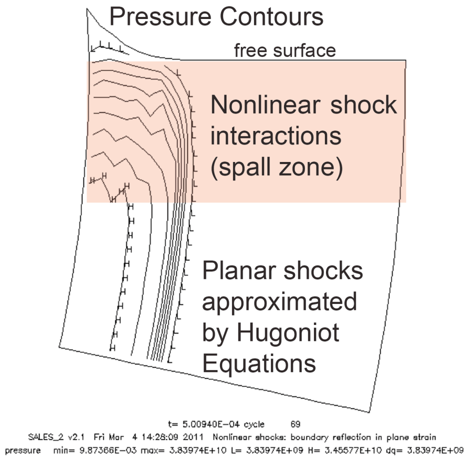

Fig. 1: Pressure contours for the shock front near the surface. The free surface boundary condition forces a pressure gradient that results in lightly shocked material (spall zone).

Ongoing Work: We will explore nonlinear shock interactions in the near surface of the target for increasingly complex target materials, including targets that fracture using the Grady-Kipp-Melosh fragmentation model. We will also model additional aspects of nonlinearity, such as the inclusion of ice and the relative importance of tensile and compressional failure in producing spall fragments. Our new analytical model for nonlinear shock interactions and spallation will be combined with fracture models to predict number, size, and velocities of spall fragments that are ejected from the surface at high speeds.

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Acknowledgements: L. O. is supported by NASA NESSF grant NNX09AU41H_S01, and H. J. M is supported by PGG grant NNX10AU88G.

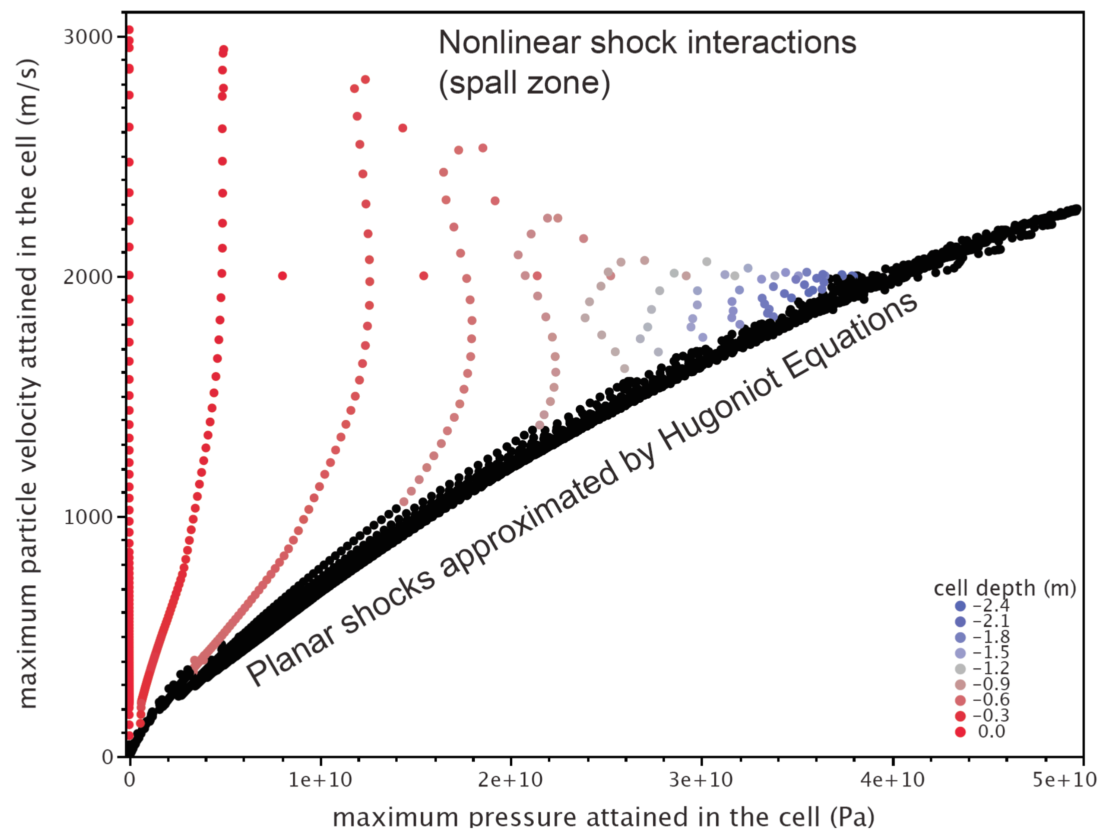

Fig. 2: Maximum particle velocity attained in each cell as a function of maximum pressure attained. Where nonlinear shock interactions occur (colored points), very high particle velocities are attained at relatively low peak pressures and the Hugoniot relations do not apply. Where the shock can be described as planar, the Hugoniot equation is valid (black points).