On Surviving Atmospheric Entry, Peter H. Schultz\(^1\) and Donald E. Gault\(^2\), \(^1\)Brown University, Dept. of Geological Sciences, Box 1846, Providence, RI 02912, \(^2\)Murphys Center of Planetology, P.O. Box 833, Murphys, CA 95247

Impactors entering planetary atmospheres undergo dynamic pressures sufficient to induce disruption and dispersal, thereby shielding the surface from impact cratering below a critical size depending on impactor composition, entry angle, and velocity (1, 2, 3). Disrupted objects approaching the minimum size for entry survival are believed to spread laterally due to interacting bow shocks (3, 4). Such a process is generally consistent with the distribution and size of craters and fragments in terrestrial crater fields (3). Laboratory experiments at the NASA-Ames Vertical Gun Range have been performed to examine this process. Lateral dispersal and rapid fragment deceleration occurs at lower atmospheric densities \((\rho/\rho_0 < 0.25)\) consistent with (3), but fragments become highly collimated without deceleration at high densities.

**Experiments:** Pyrex and aluminum spheres (0.635 cm in diameter) were shattered during passage through a thin mylar or aluminum sheet, respectively, as described in (5). The thin sheets are insufficient to decelerate the projectiles, but the induced shock disrupts the fragments into a characteristic pattern. Witness plates placed on the target surface recorded the resulting random fragmentation pattern spread over a well-defined circular area 9.0 cm in diameter (vacuum conditions). Different atmospheric gases were introduced in order to assess the effect of density and mach number on the deceleration and dispersion of the fragments. Velocity of impactor fragments during atmospheric passage were measured from high frame rate photographs (25,000 frames per second).

As atmospheric density increased from 0.125 to 0.25 bars (argon), over-all dispersion of the six largest fragments progressively increased from 6 to 7.5 cm, significantly larger than the 5 cm under vacuum conditions (Fig. 1a, b). At 0.125 bars (argon), the dispersion limit of the smaller fragments spread over 40 cm (5 times larger than the vacuum). At 0.25 bars (argon), dispersal increased further, but in addition, the four largest pits were each encircled by a tight cluster of tiny pits (Fig. 1c). At nearly full atmospheric pressure (0.9 bar, argon gas), only a single large hole was formed in the witness plate (Fig. 1d). Again, however, it was surrounded and superposed by a dense pattern of much smaller pits—just opposite to the expected pattern. The resulting hole (1.20 cm) was 15% smaller than that produced by an unbroken pyrex projectile under vacuum conditions. Use of helium atmosphere at 0.9 bar, however, resulted in a dispersal pattern very similar to lower atmospheric pressures of argon. High frame-rate photography revealed that the primary mass of projectile fragments underwent little deceleration prior to impact (Fig. 2). Small fragments separated from this mass, however, were observed to rapidly decelerate consistent with theoretical considerations.

**Discussion:** These unexpected results indicate that lateral dispersal of a cloud of projectile fragments passing through an atmosphere depends on atmospheric density and mach number. Under lower atmospheric densities, lateral velocities initiated during fragmentation allow bow shock interactions and dispersal. High atmospheric densities, however, appear to result in the entire debris cloud acting as a coherent mass surrounded by a single bow shock front. Rather than dispersing the cluster fragments, the bow shock actually contains them. Such an explanation would be consistent with the observed minimal deceleration (Fig. 2). At the velocities used (3-5 km/s), the mach cone becomes so acute that it is better described as a mach column. It is proposed that the debris cloud within the mach column continuously change shape in order to minimize aerodynamic drag. The resulting fragment mass forms a conical front with a trail of debris. This provides an extreme case of mechanical deformation of a solid body modeled in (6). Consequently much smaller fragment can survive atmospheric passage with minimal deceleration.

**Implications:** Peak pressures created during entry into the atmosphere of Venus will exceed the strengths of most asteroids and comets. These experiments suggest a process by which even fragile comets and fragmented bodies could successfully survive entry without diminishing velocity provided that break-up occurs at a sufficiently low altitude. Moreover, it is proposed that small satellite craters commonly found around 20-30 km craters may not be secondaries but are the result of pieces of the primary impactor shielded from full dynamic stresses within the mach column.

Figure 1. Effect of atmospheric density on dispersion of a cloud of hypervelocity impactors. Under vacuum conditions (Fig. 1a), the disrupted impactor forms a tight pattern. Under 0.125 bars of argon (Fig. 1b), the dispersion of smaller fragments increases. Under 0.25 bars (Fig. 1c), the smaller fragments appear to become clustered around the five largest fragments. At one bar (Fig. 1d), the entire cluster forms a collimated beam of debris.

Figure 2. Deceleration of a solid and disrupted aluminum sphere along the trajectory. The disrupted cluster shows deceleration characteristic of a solid. Small fragments isolated from the main mass decelerate as expected.