EVIDENCE FOR ATMOSPHERIC EFFECTS ON MARTIAN CRATER SHAPE; P.H. Schultz, Department of Geological Sciences, Brown University, Providence, RI 02912.

Introduction: An atmosphere affects the over-all cratering efficiency by adding an ambient pressure to the lithostatic overburden (1, 2, 3), reducing the ballistic flow of ejecta (3, 4), and modifying the coupling between impactor and target (4, 5). Laboratory experiments using the NASA-Ames Vertical Gun Range also reveal that the presence of an atmosphere introduces systematic changes in crater shape. Such changes can be understood in terms of modification of crater growth, and dimensionless scaling relations indicate that the observed laboratory-scale phenomena should be identifiable at planetary scales. As a test, the laboratory results are applied to Mars where eolian processes can produce a fine-grained substrate leading to modification by drag deceleration without the complicating effects of ambient pressure and projectile-atmosphere interactions.

Laboratory Results: Separate contributions summarize the approach and results for atmospheric modification of over-all cratering efficiencies observed in the laboratory (3, 4). Here, we focus on atmospheric effects on crater shape expressed in terms of apparent crater diameter and depth. Laboratory experiments (e.g., 6) and finite-element models (e.g., 7) reveal that impact craters under vacuum conditions first grow hemispherically and then expand laterally after achieving a maximum depth. Most of the impact displaced mass occurs at late stages during lateral expansion until gravity or target strength limits further growth. Consequently, the role of ambient atmospheric pressure or aerodynamic drag on cratering efficiency should be expressed principally by a reduction in crater diameter, rather than depth. The possible role of the projectile wake (4) is not considered here. The combined effects of atmospheric pressure and drag on crater shape can be written as:

$$\left(\frac{D_A}{d_A}\right)\left(\frac{P_o}{\delta\, v^2}\right)^{\beta/2} \sim \left(\frac{d}{g}\right)^{-\alpha/2}$$

where D_A and d_A are the observed diameter and depth, respectively, under atmospheric conditions; P_o, the ambient pressure; δ the bulk target density; v, impact velocity; d, drag deceleration on ejecta; and g, gravitational acceleration. The exponents β and α are derived for over-all cratering efficiency; a square root (rather than cube root) dependence is used due to the effect solely on diameter, not depth and diameter.

As a test, Figure 1 shows the change in diameter and depth as a function of ambient pressure alone. This is possible because the range in values for the dimensionless ambient pressure parameter in the laboratory for compacted pumice targets far exceeds the available range for aerodynamic drag. Figure 1 reveals three important trends. First, crater diameter decreases with increasing values of $P/\delta v^2$ with a power-law consistent with $-\beta/2$. Second, crater depth is essentially constant. And third, systematic offsets dependent on gas composition indicates that a residual factor related to aerodynamic drag may be hidden. If crater shape is now corrected for ambient pressure effects, then evidence for drag can be tested. Figure 2 includes two alternative expressions for d/g: the first expression uses a constant drag coefficient over a narrow range (<15%) of Reynolds numbers, R_e (upper half, Fig. 2); the second, a broad range in R_e where the drag coefficient depends on $1/R_e$. Both data sets confirm the predicted power-law dependence where α represents the exponent derived for vacuum conditions when g dominates.

It is emphasized that these results apply only to compacted pumice. Such a target exhibits a large angle of internal friction, thereby preserving the transient crater shape. Impacts under vacuum conditions reveal, however, that the target exhibits gravity-controlled growth similar to sand with an exponent of $\alpha = 0.518$. Use of loose sand targets with a low internal angle of friction exhibit rim collapse and shallowing after achieving a crater aspect ratio similar to compacted pumice.

Planetary Signatures: Although the Earth and Venus seem to provide the most ideal environments for testing such predictions, all three pressure effects acting simultaneously (further complicated by modification, erosion, and imaging) lessen their usefulness as an initial test. Mars, however, provides ideal conditions for considering just the effects of drag, even under its presently tenuous atmosphere (8). Extrapolating conditions leading to $(d/g) \succeq 0.5$ from the laboratory to current martian conditions predict that drag-modified scaling should become important for craters larger than 1 km in diameter formed in substrates producing sand-size (~500μ) ejecta. Larger craters should show a progressively deeper profile up to diameters exceeding an atmospheric scale height and/or the onset of rim/wall collapse limit. The current martian atmosphere is nevertheless too tenuous to result in significant scaling changes due to either static ambient pressure or the impactor wake. Consequently, crater depths were measured for different diameter craters formed in contrasting lithologies in order to isolate the one remaining variable, ejecta size.

Previous studies revealed the enigmatic relation between crater depth and diameter on Mars (9, 10): depths of complex craters at a given diameter exhibited considerable variation; depths of simple craters appeared to increase more rapidly than diameter; and systematic differences were recognized between craters on plains (volcanic combined with other origins) and highlands. These differences were generally attributed to the role of volatiles, whether enhancing crater collapse (10) or impact vaporization (9). Here, depth–diameter relations are contrasted between plains of well–established volcanic origin (Lunae Planum, Syrtis Major Planitia, lava flows) and probable sedimentary origin (easily eroded unconformable deposits and the fractured plains of Casius). Figure 3 reveals that this approach significantly reduced the dispersion in data for a given lithology. Moreover, craters on the fractured plains exhibit systematically deepening craters with increasing diameter. The laboratory results predict that crater growth unaffected by aerodynamic drag should exhibit d ~ D up to the onset of rim/wall collapse or other scaling changes. Crater growth affected by drag, however, should increase as $(1 + \alpha/2)$ for craters larger than a critical size (D_{At}) dependent on ejecta size for a given atmospheric density. From laboratory–based scaling relations, α is about 0.5, and Figure 3 includes the resulting slope of 1.25 fit to the data. The resulting intercept corresponds to a mean ejecta size approximately 80μ, a value consistent with a sedimentary origin. The absence of a departure for craters on volcanic plains indicate a mean size exceeding 0.2 cm.

Concluding Remarks: While previous studies proposed that the observed diameter–depth relations on Mars may require water–saturated substrates in order to enlarge crater diameters and reduce depths (9, 10), this study suggests that drag scaling controlled by the size distribution in the substrate reduces diameter while maintaining depth for simple craters. Such a proposal is consistent with predictions from laboratory experiments, the narrow dispersion in observed diameter–depth data for clearly distinguished lithologies, and the clear contrast between lithologies likely characterized by coarse (basalts) and fine (sediments) ejecta. The observed effects are reflected in crater statistics and may provide a means to identify changes in atmospheric conditions through time as well as probing physical characteristics of impacted substrates.

References: (1) Herr, R.W. (1971) *NASA TRR–366*. (2) Holsapple, K.A. (1980) In *Proc. Lunar Planet. Sci. 11th*, 2379–2401, Pergamon, N.Y. (3) Schultz, P.H (1988) *Lunar and Planet. Sci. XIX*, LPI, Houston, 1039–1040 (4) Schultz, P.H (1990) *Lunar and Planet. Sci. XXI*, LPI, Houston (this volume). (5) Gault, D.E. and Sonett, C. (1982) In *Geol. Soc. Amer. Sp Paper* 190, 69–92. (6) Gault, D.E. *et al.* (1968) In *Shock Metamorphism of Natural Materials* (B.M French *et al.*), Mono Books, Baltimore, 87–100. (7) Orphal *et al.* (1980) In *Proc Lunar Planet. Sci. Conf. 11th*, 2309–2323, Pergamon, N.Y. (8) Schultz, P H. and Gault, D .E. (1979) *J. Geophys Res.* 84, 7669–7687. (9) Cintala, M and Mouginis–Mark, P. (1980) *Geophys. Res. Letts.* 7, 329–332. (10) Pike, R.J. (1980) In *Proc Lunar Planet. Sci. Conf. 11th*, 2159–2189, Pergamon, N.Y.

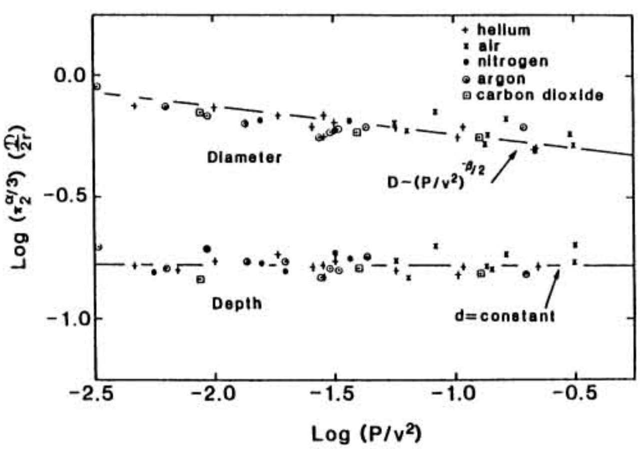

Figure 1. Effect of ambient atmospheric pressure, P, on crater diameter, D, and depth, d, for impacts into compacted pumice for different atmospheric compositions. Diameter and depth are given relative to vacuum conditions (π_2). Pressure can be given in a dimensionless form as $P/\delta v^2$ (δ is bulk target density and v is impact velocity) which varies as P/v^2 for a given target.

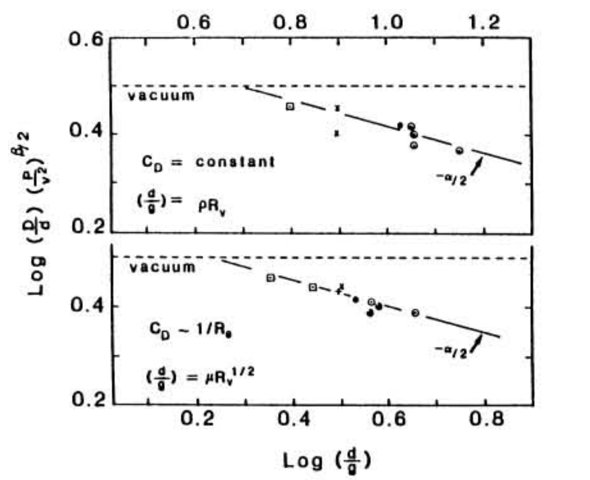

Figure 2. Effect of aerodynamic drag, d, relative to gravitational acceleration, g, on crater shape corrected for atmospheric pressure effects (Figure 1). Top half shows data over a narrow range of Reynolds numbers such that the drag coefficienct (C_D) is essentially constant, thereby resulting in d/g depending on atmospheric density and crater size, R_v, had it formed in a vacuum. Bottom half includes a broader range of Reynolds numbers such that the drag coefficient varies inversely with Reynolds number. In this case, d/g can be reduced for convenience to varying with $R_v{}^{1/2}$ and viscosity (μ).

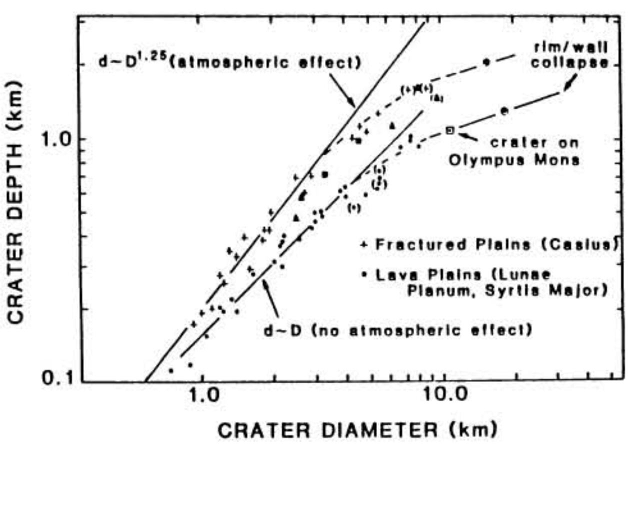

Figure 3. Depths and diameters for well–preserved craters on clearly identified volcanic plains and probable sediments. Squares indicate craters on the sedimentary fill of Isidis, while triangles indicate data for unconformable and friable airfall deposits. Parentheses and circles represent craters exhbiting partial and extensive rim/wall collapse. The clear separation of the data can be interpreted in terms of drag–controlled crater growth for probable sedimentary lithologies contrasted with no drag effects on lava lithologies.