Atmospheric Containment of Crater Growth. Peter H. Schultz and Olivier S. Barnouin, Department of Geological Sciences, Brown University, Providence, RI 02912.

The presence of an atmosphere can dramatically reduce cratering efficiency in particulate targets in the laboratory, provided that critical values of dimensionless static and dynamic pressure ratios are exceeded (1, 2). Although these dimensionless ratios also accommodate diverse empirical combinations of atmospheric, projectile, and target variables, they do not provide a clear model for the process. Here we explore a model where the atmosphere dynamically decelerates outward motion of the ejecta curtain, thereby shutting down crater growth somewhat analogous to the role of gravity.

Laboratory Experiments: Reduction in cratering efficiency has been shown (1, 2) to depend on a dimensionless Euler number ($P/\delta v^2$ for ambient pressure P, bulk target density δ, and impact velocity v) and a dimensionless ratio of aerodynamic drag to gravity forces acting on individual particles comprising the target ($d/g = 1/2C_D\rho v_e^2/\delta ga$ for drag coefficient C_D, atmospheric density ρ, ejection velocity v_e, target particle density δ, gravity g, and particle size a). Cratering efficiency includes both crater diameter and depth. Laboratory experiments reveal, however, that atmospheric forces reduce crater diameter but not depth (3). This process is preserved in targets with sufficient internal cohesion (e.g., pumice) to retain the unstable crater profile. Nevertheless, it is also clearly documented in quarter-space experiments using particulate targets with very low strength. The outward limit of crater growth temporarily matches growth for impacts into pumice but the crater subsequently collapses to a shallow profile (3, 4). Consequently, atmospheric forces restrict the gravity-controlled ballistic excavation stage of crater growth with strength playing only a secondary role.

Crater growth in water (5) closely resembles growth in low-strength particulates. Because water is not a particulate, the dynamic forces must act on the entire cratering flow field, not just individual particles. These observations led to a conceptual model where the coherent portion of the ejecta curtain resembles an inclined plate moving outward against a viscous medium (4). In such a model, the lower portion of the curtain transmits hydrostatically the forces retarding an incompressible inertial flow field. A simple analytical model illustrates some key aspects. Deceleration of a flat plate from an initial velocity v_o to a value v_x is simply expressed by:

$$ln(v_x/v_o) = -C_D\rho X/m_A \qquad (1)$$

for a distance traveled X and curtain mass in a unit area m_A. Crater ejecta do not come out in a single massive block but comprise a relatively thin curtain having a large surface area at a given time. Curtain mass in a unit area is proportional to $\delta_e W_e$ for a curtain width W_e and bulk density δ_e. Because X depends on crater radius R and because W_e at a given time will map out as ejecta thickness, t_e, at a corresponding given ballistic range, the right side of equation (1) is proportional to $-C_D\rho(R/t_e)$. Since t_e depends on $(gR)^{1/2}$, equation (1) becomes $-C_D\rho(R/g)^{1/2}$. When v_x in equation (1) reduces to a limiting value, lateral crater growth ceases. The relative importance of shut-down should actually increase as $R^{1/2}$ for a given atmospheric density. This counter-intuitive result is simply analogous to the contrasting drag effects on a small brick and a large thin sheet (or a boulder versus a glider) of equivalent mass.

Model: A model of ejecta curtain thickness through time provides a more realistic assessment of possible dynamic pressure effects on crater growth. The ejecta curtain was assumed to be a frustum of a cone that widens with time at a rate constrained by computational and analytical models of crater growth (6, 7). The ejecta flux within the frustum surface was further constrained by matching the excavated ejecta mass at a given time to the mapped ejecta thickness decaying with distance. A Runge-Kutta iteration scheme generated a 2-D (but axisymmetric) model of ejecta curtain evolution with cumulative errors less than 1% for ballistic emplacement in a vacuum. Curtain height varied as a function of time and was considered "porous" to the atmosphere (unaffected by drag forces) when the curtain width reduced to only two ejecta particles thick; consequently, curtain height depends on the size and density of ejecta particles comprising the target.

Figure 1 shows the results for curtain deceleration for No. 24 sand and pumice (or microsphere) targets under vacuum conditions and at a one bar atmosphere at laboratory scales (final apparent crater diameter of 20 cm). The coarse, porous sand is hardly affected by the atmosphere. Curtain deceleration for the pumice target, however, essentially ceases when the crater has expanded to only 75% of its final diameter, or about a factor of two in cratering efficiency. Both results are consistent with empirical observations (2). While craters in pumice retain this arrested limit, craters in microspheres collapse. As a test for the assumption that deceleration of the ejecta curtain can transmit this information to crater growth, a solid plate was placed at different heights above the target surface. The projectile passed through a hole in the plate, and ejecta during crater formation were deflected laterally away from the cavity. The resulting crater was arrested in lateral growth, just as in cratering in an atmosphere, even without any evidence for fall back.

Implications: Atmospheric reduction in cratering efficiency is proposed to represent dynamic deceleration on an incompressible cratering flow field represented by the ejecta curtain during growth. This process is controlled by the pressure difference in front of and behind an impermeable curtain, which exhibits a large surface area but

Atmospheric Containment of Crater Growth, P.H. Schultz and O.S. Barnouin

relatively little mass at any given time. Because permeability depends on the number of ejecta particles per unit volume within the curtain at any given time, cratering efficiency will depend on size, density, and velocity of individual particles comprising the curtain as well as atmospheric density. Such a perspective helps to resolve the dilemma that air drag does not prevent individual particles from being ballistically ejected (6), yet their parameters are observed to be important (2). Moreover, it allows for atmospheric reduction of crater growth in non-particulate targets (e.g., water). For purposes of illustration, Figure 2 shows the possible implications for crater growth in different planetary settings at larger scales, without inclusion of other complicating effects (see 8, 9). The atmospheres of Mars and the Earth are insufficient to limit crater growth, whereas the atmosphere of Venus could have a significant effect. This is consistent with the anomalously high rim profiles and unexpected diameter/depth relations.

(1) Schultz, P.H. (1988), *Lunar Planet. Sci. XIX*, 1037-1038. (2) Schultz, P.H. (1992), *J. Geophys. Res., 97*, 975-1005. (3) Schultz, P.H. (1990), *Lunar Planet. Sci. XXI*, 1097-1098. (4) Schultz, P.H. (1993), *Int. J. Impact Eng.,14*, 659-670. (5) Gault, D.E. & Sonett (1982), in *Geol. Soc. Amer. Sp. Bull. 190*, pp. 69-92. (6) Schultz, P.H. and Gault, D.E. (1979), *J. Geophys. Res., 84*, 7669-7687. (7) Schultz *et al.* (1981), in *Multi-Ring Basins*, pp. 181-195, Pergamon, NY. (8) Ivanov et al., (1986), *Proc. Lunar Planet. Sci. Conf. 16th, J. Geophys. Res., 91*, D413-D430. (9) Schultz, P.H. (1992), *J. Geophys. Res., 97*, 16,183-16,248.

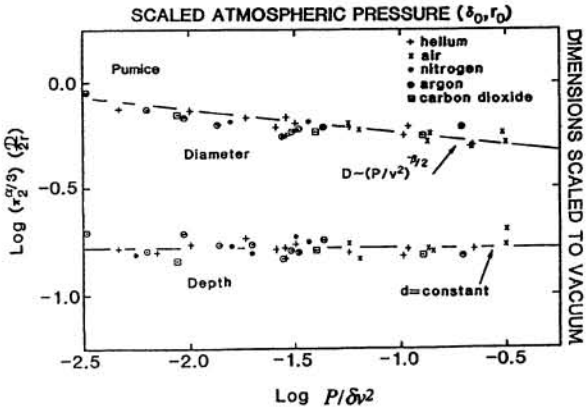

Figure 1. Effect of atmospheric pressure on crater diameter and crater depth. Dimensionless pressure is given by an Euler number with pressure *P*, bulk target density δ, and impactor velocity *v*. Pressure reduces crater diameter, not depth. The same reduction occurs in targets of microspheres and water with little or no strength but the cavity collapses after formation. Particle size, however, also has a profound effect (2) by controlling the permeability of the ejecta curtain.

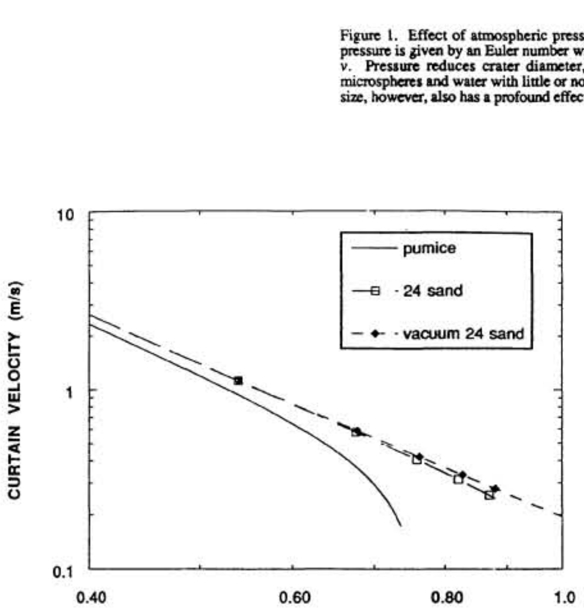

Figure 2a. Calculated dynamic deceleration of ejecta curtain created by impacts into targets with particle sizes for pumice and No. 24 sand. The ejecta curtain composed of coarse No. 24 sand exhibits little deceleration due to its high permeability, whereas the less permeable curtain of finer grained pumice rapidly decelerates after the crater has grown to 75% of its final diameter under vacuum conditions.

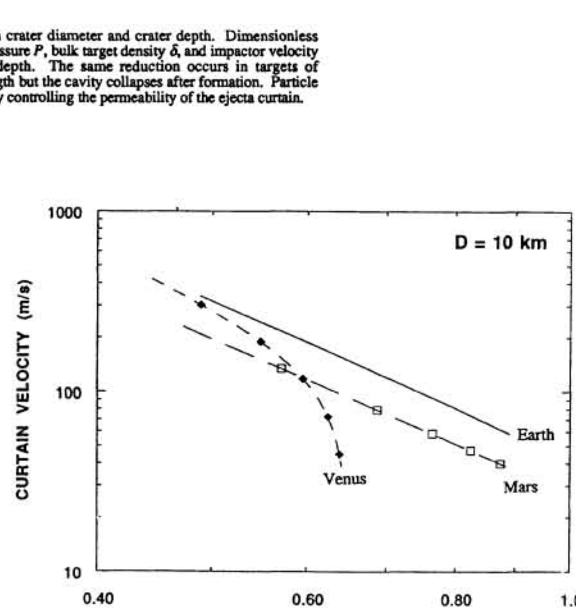

Figure 2b. Dynamic deceleration of ejecta curtains for 10 km-diameter craters on Mars, Earth, and Venus. Dynamic forces are insufficient to decelerate curtains (crater growth) on either Mars or Earth but could have a profound effect on Venus. Although the total ejected mass is large relative to the atmosphere, dynamic retarding forces at any given time are large due to the large outward velocity and large surface area of the curtain. Even supersonic velocities experience significant retarding forces.