ATMOSPHERIC EFFECTS ON IMPACT CRATERING EFFICIENCY; P.H. Schultz, Dept. Geological Sciences, Brown University, Providence, RI 02912.

The effect of atmospheric pressure on impact cratering is widely believed to decrease with increasing crater size as lithostatic overpressures increasingly overwhelm ambient atmospheric pressures (1, 2). Recent experiments, however, indicate that static atmospheric pressure represents only one of at least three effects of an atmosphere. Two other effects include the response of crater growth to dynamic pressures acting on the wall of outward-moving ejecta and dynamic pressures acting on individual ejecta within the curtain.

Impact experiments were performed at the NASA-Ames Vertical Gun Range, a national facility supported by NASA's Planetary Geology and Geophysics Program. Targets included compacted pumice with a bulk density of 1.50 gm/cc and particles smaller than 100 μ (modal size of about 50 μ) and No. 140-200 sand with a bulk density of 1.46 gm/cc (grain sizes between 105 μ and 125 μ). After gradual evacuation of the chamber, a variety of ambient gases were introduced including helium, nitrogen, argon, and carbon dioxide. Launch velocities for 0.0159-0.635 cm spheres ranged from 0.5 to 6.5 km/s. The impact chamber was isolated from the launch tube by a thin mylar diaphragm; actual impact velocities were estimated from standard drag formulae from this entry point to the target.

The effect of an atmosphere on cratering efficiency can be expressed in the following terms:

$$\left(\frac{M}{m}\right) \sim f_s \cdot f_e \cdot f_d \cdot \left(\frac{M}{m}\right)_v \qquad (1)$$

where (M/m) and $(M/m)_v$ represent the cratering efficiency for different environments (pressure, gas composition) and vacuum conditions, respectively; dimensionless functions incorporate the effects of static atmospheric/lithostatic overburden (f_s), dynamic pressure acting on individual ballistic ejecta (f_e), and dynamic pressure acting on the outward-moving ensemble of ejecta, i.e., the ejecta curtain (f_d).

The atmospheric/lithostatic overburden can be expressed as $\sim (P_s/\delta_t gh)^{\beta}$ for $P_s >> \delta_t gh$ where P is the static ambient pressure; g, the gravitational acceleration; δ_t, the target density; and h, a characteristic depth which is related to the potential crater dimensions had it formed in a vacuum. This relation is typically used to describe static atmospheric effects on cratering efficiency (1, 2, 3). Figure 1 reveals that this term alone, however, does not adequately accommodate the observations.

The effect of air drag acting on an individual ejecta particle is given in dimensionless form as $(1/2 C_D \rho v_e^2/\delta_o ga)^{\gamma}$ for $1/2\, C_D \rho v_e^2 >> \delta_o ga$ where C_D is the drag coefficient; ρ, the density of the ambient atmosphere; v_e, the velocity of the ejecta; δ_o, the density of an ejecta fragment; and a, the ejecta size. The value of the drag coefficient for the laboratory experiments depends on the Reynolds number owing to the relatively low ejection velocities and small ejecta sizes.

A helium atmosphere has little effect on the observed ejecta curtain yet results in a significant decrease in the cratering efficiency. This observation is used to isolate the effect of atmospheric pressure and to determine the power-law exponent, $\beta = -1/4$. Correcting the observed data for the effects of static atmospheric pressure in a helium atmosphere provides a means to determine the effects of air drag in a given atmosphere of higher density (CO_2, Ar, N_2). Such an approach revealed a further dependence on the viscosity of the ambient atmosphere that is interpreted as the remaining effect (f_d) of the atmosphere acting on the outward-moving ejecta plume, an interpretation based on the belief that an outward-moving viscous sheet will experience drag even if it is not composed of discrete ejecta. The effect of the atmosphere on the moving ejecta curtain can be expressed as $f_c \sim \Delta P/\delta_e gC$ for $\Delta P >> \delta_e gC$ where ΔP is the pressure differential inside and outside the ejecta curtain; and δ and C, the density and characteristic dimension of the ejecta curtain, respectively. The value for ΔP draws on an analogy with permeability that reflects the ability for the atmosphere to reach the region behind the curtain by inflow from above and is taken to be a constant. The resulting expression for the effect of the moving wall of ejecta can be shown to depend on $\mu\sqrt{R}$ where μ is the permeability and R_v is the size of the crater had it formed in a vacuum. Applying this factor to the observed data largely eliminates systematic variations dependent on impact or environmental conditions.

The following relation between atmospheric effects and cratering efficiency is derived from the empirical relations and cratering models relating late-stage ejection velocities to crater size (e.g., 4):

$$\frac{M}{m} \sim \left(\frac{P_s}{\delta_t gR}\right)^{-1/4} \cdot \left(\frac{\mu}{\rho}\right)\left(\frac{\delta_o}{\delta_e}\right)\left(\frac{a}{C_D R_v^{1/2}}\right) \cdot \left(\frac{M}{m}\right)_v \qquad (2)$$

Figure 2 shows the effect of incorporating the derived dynamic pressure functions (f_e and f_d) on the

systematic trends observed in Figure 1. The remaining offset between pumice and sand reflects contrasts in ejecta size since target densities and porosities are similar. Equation 2 only applies for the condition where all pressure terms are important, as on the Earth and Venus for sufficiently large impacts with small ejecta. On Mars, the power-law function for f_S is unimportant for present conditions, whereas on Venus it would affect craters smaller than 0.5 km if the impactors survived entry. The effect of aerodynamic drag, however, can become important even on Mars as crater size (average late-stage ejection velocity) exceeds a limiting diameter. As the crater exceeds several atmospheric scale heights, however, atmospheric density and its effect on cratering efficiency decreases.

Further experiments are necessary to confirm the derived dependences over a broader range of impact scales and to determine the limiting fraction of small ejecta that can affect cratering efficiencies. Nevertheless, the trends implied from equation (2) may have important implications including the interpretation of chronologies on planets with atmospheres.

(1) Chabai, A. J. (1977), in *Impact and Explosion Cratering*, (D. Roddy, R.O. Pepin, R. B. Merrill, Eds.), Pergamon, N.Y., 1191–1214. (2) Holsapple, K. A. (1979). *EOS (Trans. Amer. Geophys. Union) 60*, 871. (3) Herr, R.W. (1971), *NASA-TRR-366*, NASA Langley Research Center, Hampton, VA. (4) Schultz, P.H. and D.E. Gault (1979), *J. Geophys. Res. 84*, 7669–7687.

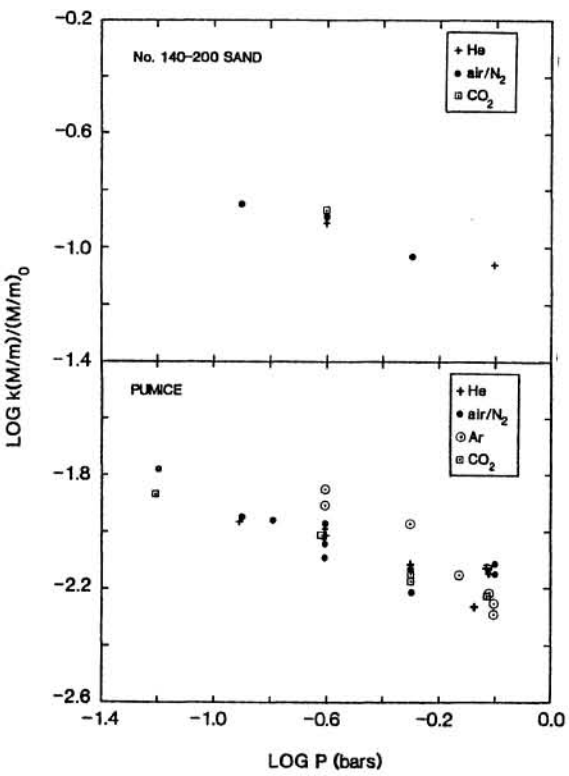

Figure 1. The effect of atmospheric pressure (in bars) on cratering efficiency (M/m) in sand and pumice referenced to the efficiency predicted for the same impact conditions in a vacuum $(M/m)_v$. The factor k depends on the scaling relations established for each target under vacuum conditions.

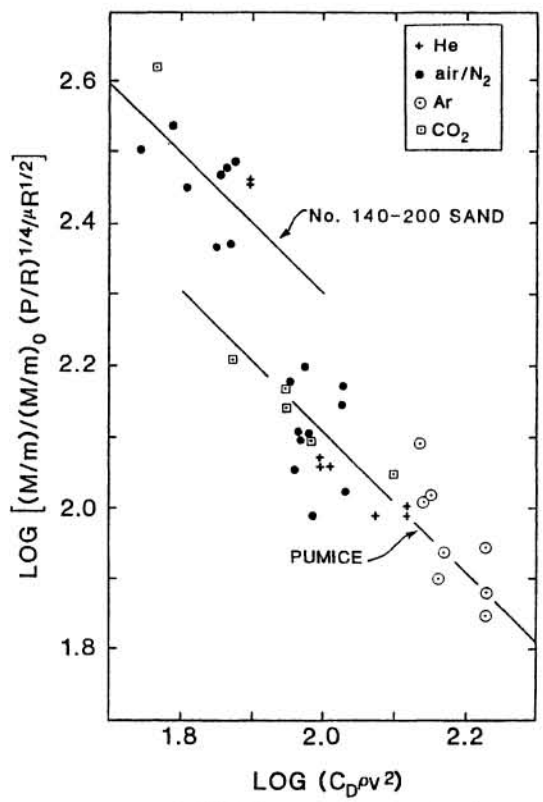

Figure 2. Relative cratering efficiency normalized to vacuum conditions and corrected for the effects of pressure acting on the moving ejecta curtain and individual ejecta as a function of atmospheric/lithostatic overburden. If the contrast in density and the difference in grain size between sand and pumice were included, the two sets of data would merge.