ATMOSPHERIC EFFECTS ON IMPACT CRATERING EFFICIENCY

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Introduction: The efficiency of explosion cratering has been shown to be dramatically reduced for sufficiently large ratios of atmopheric pressure to lithostatic overburden (1, 2). The efficiency of impact cratering in an atmosphere previously indicated only a minor effect (3). However, ongoing experiments at the NASA-Ames Vertical Gun (3, 4) indicate that atmospheric pressure can drastically reduce the cratering efficiency for sufficiently fine-grain target material. These results have important implications for comparing energy-diameter scaling relations derived for very fine-grain targets under ambient atmospheric conditions. Moreover, a revised dimensionless atmosphere-dependent scaling parameter is independent of crater dimension, thereby having implications for impacts on planets with atmospheres.

Experimental Conditions: A series of impacts with the NASA-Ames light-gas and powder guns provided a range in velocities from 0.6 km/s to 6.5 km/s. Hypervelocity impacts ($>$5 km/s) used 0.635 cm aluminum spheres; supersonic ($<$3 km/s) impacts used 0.635 cm or 0.159 cm aluminum spheres and 0.635 cm pyrex spheres. The target material was dry, very fine pumice with estimated median particle sizes about 40μ and dry, fine quartz sand with median particle sizes about 90μ. Supersonic impacts were made in air with atmospheric pressures from 1.5 mm to 760 mm (Hg), whereas hypervelocity impacts used either nitrogen or argon with pressures from 1.5 mm to 720 mm (Hg). This range in projectile, target, and atmospheric parameters permitted differentiating independent scaling parameters. Launch velocities were recorded by photobeams prior to entry in the impact chamber. Impact velocities at the target were reduced by using well-established aerodynamic drag formulae. A thin mylar diaphragm prevented large ambient gas pressures in the impact chamber from entering the launch chamber prior to launch and suppressed muzzle blast effects..

Results: The experiments were initially designed to evaluate the dynamics of ejecta/atmosphere interactions (4, 5) but revealed in addition systematic and repeatable changes in crater morphology (6) and crater size (7). Hypervelocity impact craters in pumice showed a progressive decrease in crater diameter as atmospheric pressure increased, whereas crater depth remained relatively constant (Figure 1). Crater diameter and displaced mass produced under 720 mm atmospheric pressure of argon were reduced to only 36% and 13% of the values, respectively, produced under 1.5 mm of air for approximately the same impact velocity (6.1 km/s corrected for air drag). In contrast, the crater depth under nearly full atmospheric pressure was reduced to 86% of the depth under near-vacuum conditions. The same trends were recorded for all variations in projectile parameters (velocity, size, density). Impacts in the coarser, fine quartz sand were systematically larger than craters in pumice under atmospheric conditions and approached values typical of near-vacuum conditions. Nevertheless, they displayed a small but significant decrease in dimensions with increase in atmospheric pressure.

In order to understand these trends, the effects of impact velocity, gravity, projectile size, and target differences must be normalized as in (8). The gravity-scaled parameter, 3.22 (gr/v^2), includes the effects of gravity, g, projectile radius, r, and impact velocity, v and is related by a unique power law to the cratering efficiency (displaced-mass/projectile-mass) for the same target and atmospheric conditions (8). Previous experiments, with impacts indicated a reduction in cratering efficiency by only 20% relative to vacuum conditions (9). The present experiments, however, indicate that impacts in pumice under 720 mm (Hg) of argon, reduce the cratering efficiency

by 750%. If the reduction in cratering efficiency were due to an effect of trapped air in the target, then a large difference in the displaced mass would exist between near-vacuum impacts in sand and pumice. This is not observed. If it were due to energy dissipation by atmospheric gases in the projectile bow wave, then there would be a significant decrease in projectile penetration and a projectile velocity effect. These phenomena are not observed.

Experiments in explosion (2) and impact (9) cratering previously have used the dimensionless atmospheric scaling parameter ($P/\rho gd$) where P is the atmospheric pressure, ρ is the target density, g the gravitational acceleration, and d an effective radius (depth of burst for explosion and projectle radius for impacts). The present experiments, however, suggest that this expression is not adequate: no projectile radius dependence is observed and it does not include a particle size dependence. A revised dimensionless atmospheric scaling parameter appears to account for the observations: ($C_D \rho_o v^2/\rho gl$) where the new variables, C_D, ρ_o, v, and l are the drag coefficient (dependent of Reynolds number), atmospheric density, ejecta launch velocity, and particle size, respectively. The scaling relation ($P/\rho gd$) physically compares the static condition of atmospheric pressure and lithostatic overburden. The proposed scaling relation ($C_D \rho_o v^2/\rho gl$) physically compares the dynamic condition of dynamic air pressure and lithostatic pressure on a particle in a ballistically controlled ejecta flow field. This revised scaling relation has not been recognized in explosion cratering due to the static nature of the source, but the same trend exists in the data (2) for shallow depths of burst. It has not been recognized in previous impact experiments because particle sizes in the target were too large.

Implications: The revised scaling relation predicts that the effect of an atmosphere on cratering efficiency does not decrease with an increase in the size of the event. Moreover, for the same size *in situ* target material, atmospheric effects actually may increase with impact energy since middle and late-time ejecta velocities increase with impact energy (3). Thus modest-size impact craters (<10 km) produced on the Earth, Venus, and Mars may be systematically smaller than craters produced on the Moon for the same impact energy and velocity.

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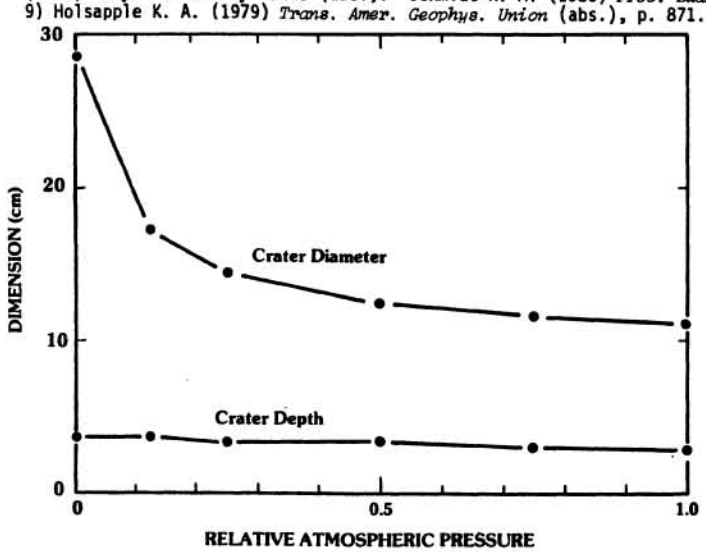

Figure 1. Comparison of diameter and depth for craters produced under different atmospheric pressures of argon by 0.635 cm aluminum spheres impacting at about 6km/s.