JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 97, NO. E1, PAGES 975–1005, JANUARY 25, 1992

Atmospheric Effects on Cratering Efficiency

PETER H. SCHULTZ

Brown University, Providence, Rhode Island

Laboratory experiments permit quantifying the effects of an atmosphere on cratering efficiency by hypervelocity impacts. Three separable processes have been identified: ambient atmospheric pressure, aerodynamic drag, and projectile-atmosphere interactions. The effect of ambient atmosphere can be described by a dimensionless pressure ratio, $P/\delta v^2$ for a pressure P, target density δ, and impact velocity. The use of a helium atmosphere minimized potential effects of aerodynamic drag (low density) and projectile-atmosphere interactions (low mach numbers) and revealed a power-law exponent of -0.23 for the dimensionless pressure term for impacts into pumice. Similar exponents but different degrees of reduced cratering efficiency are observed for targets composed of loose fine-grained sand, low-density microspheres, and mixtures of coarse sand with small amounts (<10%) of fine-grained particulates. Consequently, cratering efficiency in an atmosphere does not appear to depend on material properties of the target (internal angle of friction) but on atmospheric pressure and constituent grain size. Correcting the data for atmospheric pressure allowed testing for the possible role of aerodynamic drag through the use of higher-density atmospheres (same pressure) and various targets with contrasting ejecta sizes but the same bulk density. The results reveal that the effect of aerodynamic drag deceleration d can be viewed as a correction to gravity g in the dimensionless gravity-scaling π_2 parameter. The derived power law exponent for drag-controlled crater growth in an atmosphere closely matched the exponent for gravity-controlled crater growth in a vacuum. If it is further assumed that a combination of pressure and drag jointly limit crater growth, then the empirical power law exponent reasonably matches values derived from dimensional analysis and a coupling parameter theory. After correcting for pressure and drag, systematic offsets of the data remained and appeared to depend on Mach number. The possible role of the supersonic wake trailing the projectile was tested by performing projectile-less impacts where only the wake was allowed to interact with the target. The colliding projectile wake was found to affect crater scaling in two ways. At low mach numbers, the trailing wake gases augmented cratering efficiency by creating backpressure in the transient cavity; that is, the effect of the projectile wake was decoupled from the impact and could be viewed as a negative ambient pressure. At high mach numbers, the disturbed wake gas became coupled with the impactor, thereby changing the effective size of the energy source. Both effects could be documented in the data and in observed phenomena during impact. These results not only reconcile previous studies where atmospheric pressure effects were found to be minimal but could have potential implications for interpreting the cratering record on planets with atmospheres.

INTRODUCTION

Atmospheric effects on explosion and impact cratering is thought to decrease with increasing crater size as lithostatic overpressures increasingly overwhelm ambient atmospheric pressures [see *Chabai*, 1977; *Holsapple*, 1980]. Early experiments by *Johnson et al.* [1969] using explosives showed that crater diameter varies inversely with atmospheric pressure but with an exponent of only 0.044 for pressures between 0.4 and 1.3 atm. *Herr* [1971] performed a more extensive series of experiments involving explosions buried at different depths in dry soils. The atmosphere has little effect on scaling for surface explosions, whereas it has a significant effect for buried explosions. At the optimum depth of burial of the explosive charge (i.e., maximum efficiency), crater growth occurs as expanding gases accelerate the target material, as described by *Nordyke* [1961]. Herr concluded that atmospheric pressure should have little effect on crater scaling since impact cratering events do not grow in response to expanding gases. Later impact experiments by *Holsapple* [1980] supported this conclusion by finding only a weak dependence between reduction in crater size and atmospheric pressure for sand targets. *Schultz and Gault* [1979, 1982*a*, *b*, 1984] explored the possible effects of an ambient atmosphere on ballistic trajectories coupled to first-order analytical model of crater growth. This study emphasized the potential importance of aerodynamic drag on ejecta emplacement and concluded that dynamic drag significantly modifies initially ballistic trajectories if the ejecta are smaller than a critical size that depends not only on atmospheric density but also event scale and gravity. The experiments by *Holsapple* [1980] used targets with ejecta sizes significantly larger than the critical ejecta size, thereby restricting the study to the effects of atmosphere pressure without the possible effect of drag. Other studies [*Schultz and Gault*, 1979, 1984; *Schultz*, 1982,1988*a*] employed granular targets with grain sizes smaller than the critical size for the available event scale and atmospheric pressures and found significant modification of both the emplacement process and crater scaling. The present paper re-examines the possible role of the atmosphere for crater scaling by varying not only pressure but also ejecta size and atmospheric density.

The potential effects of an atmosphere on crater scaling can be separated into independent physical processes: modification of the coupling between the impactor and target due to the compressed air cap in front of the projectile and complex interacting air shocks [see *Gault and Sonett*, 1982]; static ambient lithostatic and atmospheric overburden; and dynamic pressures acting on individual ejecta comprising the ejecta wall. These various effects are not always easily separated since they do not involve independent variables. Although it is possible to first derive groups of independent variables based on requirements for dynamic or geometric similarity, the following discussion systematically examines

Paper number 91JE02503.
0148-0227/92/91JE-02503$05.00