Wake-Blast Effects in Laboratory Experiments and on Venus, Peter H. Schultz, Dept. of Geological Sciences, Box 1846, Brown University, Providence, RI 02912

Hypervelocity objects passing through an atmosphere create an intense disturbance within the well-known mach cone. Such disturbances are commonly viewed as a cylindrically expanding shock. Laboratory experiments and craters on Venus, however, demonstrate that trailing impactor wake gases exert significant dynamic pressures. In laboratory experiments, the impinging wake contributes to crater excavation (Fig. 1) and surface scouring under high atmospheric densities (1). On Venus, the wake draws ejecta and disturbed surface debris downrange (2).

Laboratory Experiments: Three sets of laboratory experiments were designed to explore the potential importance of impactor wake blast. The experiments were performed at the NASA-Ames Vertical Gun Range at the NASA-Ames Research Center, a national facility jointly operated by NASA-Ames and the Lunar and Planetary Institute. The first series of experiments used small, very low density styrofoam balls on the pre-impact surface as tracers for the atmospheric response to 5 km/s impacts into dry compacted pumice and powdered carbonates at 90° and 30° angles from the horizontal. High frame rate imaging (8 k to 35 k frames per second) was used to record the events. Vertical impacts into pumice failed to disturb the styrofoam tracers until they were entrained in the ballistically ejected flow field. Vertical impacts into powdered carbonates, however, created a spherically expanding vapor cloud that swept away these tracers well in advance of the ejecta curtain. Consequently, an atmospheric shock created by the impactor wake was either insignificant or completely contained by the growing excavation cavity. The atmospheric response to oblique impacts into pumice, however, swept away the tracers, scourd the downrange surface, and created dunelike ripples uprange.

The second experimental series sought to isolate the wake blast from the projectile in order to assess quantitatively the limit of the scour zone. The projectile was allowed to pass through an aluminum plate and impact into a decoupled target. The plate was covered by a single-grain layer of no. 140-200 sand (model size of 125μ), and in certain experiments, styrofoam tracers. The impact chamber was filled with different gases (helium, carbon dioxide, nitrogen, and argon) in order to assess the effects of both sound speed and density. At low mach numbers (M < 6), the size of the wake-scoured zone scaled to impactor size was found to increase with the dynamic wake pressure, pv^2, for gas density ρ and impact velocity v (Fig. 2). At high mach numbers (M > 10), the scour zone increases as Pd/δw^2 where Pd is the dynamic pressure for an incompressible gas (Pd = M^2 for a ratio of specific heat γ, δw is the density of individual grains, and the wake collision velocity w is assumed to be a given fraction of the impactor velocity. Additional experiments are still needed to assess effects of grain density and surface roughness.

The power of the wake blast was most clearly revealed at oblique angles. Uprange, styrofoam tracers were driven downward into the sand layer and then outward, but once entrained were carried downrange. Transverse ripples were created uprange in the sand layer. Tracers elsewhere were simply lifted off the surface. Downrange, the wake redistributed the upper layers of sand without scouring to the metal plate base. The redistributed sand created parallel ridges extending off the edge of the plate more than 20 cm from the 5 cm aperture through which the projectile passed. Near the aperture, the blast swept away the sand completely out to 5 cm but removed a thin veneer to a comparable distance beyond the margin of this swept zone. The scour zone was asymmetric with the greatest area of removed sand uprange. This asymmetry reflects action by both the vertical and lateral components of the wake uprange but principally a horizontal component downrange. The resulting pattern closely resembled scouring of ejecta observed for oblique impacts into pumice.

The third series of experiments examined cratering efficiency by projectile-less wake blasts in various particulate targets. Cratering efficiency was expressed by displaced target mass, M, scaled to an undisturbed parcel of the ambient gas of density ρ equal to a projectile mass of density δp, i.e., (M/m_p)(δ_p/ρ)^1/3. The resulting size of the wake-blast crater was found to be a function of the dimensionless gravity scaling parameter, τ_g, with an effective source (τ_g) equal to a unit volume of the disturbed wake, i.e., τ_g = τ_g^2(τ_g^2)^3 = (pv^2/P)((γ + 1)/(γ - 1)). Consequently, loose particulate target resembled cratering by a low-density impactor (3) as shown in Figure 2.

These three experimental series serve to demonstrate the potential power of impactor wake gases at high mach numbers and high atmospheric densities. For vertical impacts in the laboratory, the colliding wake appears to play two roles. At low velocities or densities, wake gas appears to be decoupled from energy/momentum transfer from impactor to the target. Consequently, decreasing cratering efficiency with
increasing atmospheric pressure (1) can be offset by wake-blast effects. At high mach numbers and densities, impactor and wake appear to be coupled, thereby resulting in a change in the effective dimensions of the impactor. For loose particulate targets under high densities, wake effects can offset the effects of atmospheric density and aerodynamic drag. Wake gases from oblique impacts, however, are not contained by the excavation cavity and can result in considerable modification of downrange surfaces by intense winds.

**Venus Examples:** It is unlikely, however, that wake blast at these scales also modify cratering efficiency except for particulate substrates. Nevertheless, the high atmospheric density on Venus allows examining the possible effects of collisions of the impactor wake. Four distinct and clear expressions can be recognized. First, smaller craters (<20 km) formed by oblique trajectories exhibit a distinctive "fly" shape pattern of the ejecta, rather than the classical "butterfly" pattern from impacts under vacuum conditions. Many examples exhibit "wing-tips" deflected downrange, typical of atmospheric modification witnessed in laboratory experiments (4). Second, radar-bright "runways" uprange from numerous oblique impact craters and crater-less blast zone are proposed to indicate surface disruption by the pre-impact shock. Third, radar-dark materials in the lee of ridges, scarps, and fractures are consistent with redistribution and deposition of target (and impactor?) materials by wake winds. And fourth, dune fields uprange from several craters on Venus are indicative of strong wake-induced winds. Hence, the first-order processes witnessed in laboratory experiments under less extreme atmospheric conditions not only allow understanding some of the enigmatic features revealed by Magellan but also should define quantitative models.


**Figure 1.** Decreased cratering efficiency in loose, dry sand and pumice as a function of the dimensionless pressure parameter $P/d_\text{w}v^2$ for pressure $P$, target density $d_\text{t}$, and impact velocity $v$. Ordinate represents observed cratering efficiency scaled to vacuum conditions. As atmospheric density increases beyond a critical level, cratering efficiency in sand appears to increase. Symbols correspond to carbon dioxide (squares), argon (circles), air (crosses), and helium (crosses).

**Figure 2.** Effect of wake blast isolated from the impactor on scouring away a veneer of sand over a plate (Fig. 2a) and excavating a crater in a semi-infinite target (Fig. 2b). The projectile-less wake collision was created by allowing the projectile to pass through an opening without affecting the target. The radius of the blast zone ($r_b$) is scaled to the impactor radius ($r_p$). The wake blast at low dynamic pressures resembles a wind. At higher velocities, the parcel of supersonic wake gas resembles a low density impactor of radius $r_\text{p}$ and density $\rho$ (Fig. 2b).