assumed drag coefficient is valid with little scatter, as expected. For reference, observed departures in the drag coefficient from the assumed $24/Re$ for a sphere is shown. A helium atmosphere permits examining effects at higher impact velocities but low Mach numbers, and again departures are minimal but with systematically lower values for the high velocity data. Higher-density gases and higher Mach numbers show systematic differences. Specifically, impacts using air (or nitrogen) as the ambient atmosphere exhibit an increase in relative cratering efficiency at high Reynolds numbers. At a given Reynolds number, high-velocity impacts in an argon environment result in a consistently greater cratering efficiency except at the highest densities (pressures), whereas impacts under carbon dioxide appear to be lower. Low-velocity impacts into sand (Figure 11*c*) exhibit the same general trends with enhanced efficiencies at higher atmospheric densities, in contrast with the expected decrease as the drag coefficient departs from $24/Re$.

Figure 11, then, confirms the suspicions raised from Figure 9*b* that an additional, but second-order process modifies cratering efficiency. Because of the apparent dependence on atmospheric density and Mach number, this process may be related to the disturbed air mass accompanying and trailing the projectile.

Projectile-Target Coupling

An object passing through an atmosphere from supersonic ($1 < M < 5$) to hypersonic ($M \rightarrow 5$) velocities creates a bow shock in front of the projectile and a trailing disturbance contained in the mach cone. This disturbed region may modify the scaling relations derived for particulate targets under vacuum conditions. Three possibilities exist First, interaction between projectile and target at contact creates a momentary vacuum, thereby essentially decoupling the impact from atmospheric pressure (Figure 12*a*, left). Second, complex interacting shock waves created at the moment of impact modify projectile-target coupling and scaling (Figure 12*a*, middle) along the lines described by *Gault and Sonett* [1982]. And third, the standoff of the bow shock in front of the projectile or subsequent collision by the disturbed zone trailing behind the projectile may modify the cratering process (Figure 12*a*, right).

Several experiments allow contraining the relative importance of the three processes. In one experimental series, very low density styrafoam spheres were placed on the target surface near the point of impact and observed at framing rates as high as 35,000 fps. Impacts into pumice and sand failed to move these styrofoam tracers until they were incorporated in the general ejecta flow field. Impacts into volatile-rich targets, however, produced an expanding vapor cloud that swept away the tracers [*Schultz*, 1988*c*]. Consequently, it would appear that the tracers were sufficiently susceptible to passage of a shock front, but if a temporary vacuum had been created, then it was very short lived. Application of analytical solutions [*Taylor*, 1951; *Zel'dovich and Raizer*, 1967] to the laboratory-scale impacts reveals that any near-vacuum conditions are restricted to the earliest times, thereby reducing atmospheric pressure effects only momentarily.

Interacting shocks between target and projectile at early times may affect early time flow fields and ejecta trajectories (Figure 12*a*, middle) as suggested by *Gault and Sonett* [1982]. One possible consequence is a momentary increase in the overpressure. Again, this is an early time phenomenon and may not be significant for scaling at laboratory scales. Experiments nevertheless reveal a short-lived disturbance expressed as a small bulge in the ejecta curtain that moves upward with time [see *Schultz and Gault*, 1979, 1982*a*].

The third process involves the disturbed air surrounding and trailing the projectile (Figure 12*a*, right). As a supersonic ($M > 1$) sphere traverses an atmosphere, it generates a disturbed zone of trailing gas contained within the well-known mach cone. At hypersonic velocities ($M > 5$), the disturbed zone within the mach cone approaches a cylindrical shape. The wall of the cylinder represents the shock front containing high-density, high-temperature gases that expand both outward into the ambient atmosphere and inward into the rarefied region immediately behind the projectile. At laboratory scales where $M > 18$, filling of this cylinder occurs well within a projectile radius. Gas molecules within the filled cylinder retain a significant component (0.1-0.25) of the projectile velocity. Consequently, the trailing wake as well as the projectile collide with the target and may displace material.

Fig. 11. Gravity-scaled cratering efficiency corrected for atmospheric pressure and aerodynamic drag and expressed in terms of the Reynolds number for ejecta. In addition a small correction for different projectile densities has been introduced (see equation (18)). The atmospheric pressure parameter π_p is given by $(P/\delta_t v^2)\pi_2^{\alpha/3}$ from equation (10*d*). A downward departure from a single value of the corrected cratering efficiency should reflect either a departure from the assumption of $C_D \sim 1/Re$ for (d/g) as Re exceeds unity or a change in scaling. The dotted line represents the expected departure if the drag coefficient followed values for spheres. An upward departure could indicate other processes offsetting the effects of ambient pressure or drag. Figure 11*a* shows pumice data for different gases at low densities where additional processes affecting crater scaling are not expected. At low impact velocities for a variety of atmospheric compositions (Figure 11*a*, top), the pressure/drag-corrected cratering efficiency is nearly constant with a suggestion of a changing drag coefficient for Re from 0.5 to 1. For a wide range in velocities at low densities resulting from the use of helium (Figure 11*a*, bottom), a similar decrease at higher Reynolds numbers is suggested. Figure 11*b* shows data for higher density gases with contrasting impact velocities (and Mach numbers). Air and nitrogen (Figure 11*b*, top) data exhibit a nearly constant pressure/drag-corrected efficiencies but increase at higher numbers. High velocity argon (Figure 11*b*, bottom) data are systematically higher than helium even at low Reynolds numbers but rapidly decrease for $Re > 6$. The decrease may be related to ionization of argon as revealed in high frame rate photography. Both low (solid squares) and high (open squares) velocity data for carbon dioxide are systematically lower. Figure 11*c* shows data for sand and reveals a pattern similar to air and nitrogen for pumice targets. At high Reynolds numbers, cratering efficiency is significantly enhanced. The higher than expected values depend on atmospheric composition and suggest that other processes may be competing with the effects of atmospheric pressure or aerodynamic drag. Of particular concern is the apparent augmentation in cratering efficiency for the sand targets characterized by low cohesion. (Pressure/drag-corrected efficiency is given in dimensionless form; (d/g) is calculated for $C_D = 24/Re$ resulting in $12\mu v_e/\delta_t g a^2$ as discussed in the text. Density ratios have been referenced to aluminum impactors into pumice following equation (18).)