Atmospheric Effects on Ejecta Emplacement and Crater Formation on Venus From Magellan

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The Venus cratering record provides a unique environment for assessing the effects of both gravity and an atmosphere on impact crater formation. This contribution uses surface signatures of energy partitioning as a framework for testing extrapolations from laboratory experiments and other planetary settings. Seven general conclusions can be drawn. First, the dense lower atmosphere of Venus takes on the role of a low-density target for bodies smaller than about 4 km in diameter. Air blasts created by cratering in the atmosphere create distinctive surface signatures that allow the derivation of an independent assessment of impactor energy at the limit of break up. Second, dynamic pressures due to entry of larger bodies will exceed their strength limit but may not prevent penetration of the atmosphere due to aerodynamic reshaping that minimizes the drag coefficient. Such a process may account for the formation of unusually small craters (1-3 km). Third, the dense atmosphere of Venus preserves signatures of early time cratering processes on the surface that are typically lost on atmosphere-free surfaces. Such signatures not only provide another estimate of impactor energy but also include a distinctive record of the impactor (i.e., comet versus asteroid) in distinctive run-out flows created before the crater has finished formation. Strong winds and turbulence associated with the atmospheric disturbance at late times create wind streaks behind topographic barriers. Fourth, ballistic ejection of excavated debris occurs from craters on Venus just as it does on planets without an atmosphere, thereby underscoring the fundamental mechanical transfer of energy from impactor to target. Fifth, ejecta emplacement is nonballistic due to the large dynamic forces acting on the advancing curtain and its constituent ejecta. The outward moving ejecta curtain induces strong response winds that entrain ejecta and drive a ground-hugging debris flow outward without returning to the cavity. Flow separation creates an overlying run out ejecta flow further sustained by atmospheric turbulence and identified as radar dark lobate lobas. Sixth, radar-dark parabolae are proposed to be late time fallout deposits created as the downrange fireball evolves aloft, perhaps analogous to terrestrial tektite strewn fields. And seventh, the response of crater formation to the atmosphere is conversely expressed by a reduction in cratering efficiency as revealed by the unusually large central peak complexes and the unexpected diameter-depth relations of craters. Hence surface ages may be significantly underestimated.

1. INTRODUCTION

Relatively few detailed studies have focused on the role of an atmosphere in modifying crater formation and ejecta emplacement [e.g., Schultz and Gault, 1979, 1982, 1983; Schultz, 1989, 1990a, b, 1991a, b, c, d; Melosh, 1981; O'Keefe and Ahrens, 1982a]. Although the possible catastrophic consequences of major impacts on the atmosphere and biosphere on the Earth have stimulated research on such possibilities, aspects concerning energy partitioning to the atmosphere [as found in conference proceedings edited by Silver and Schultz, 1982; Sharpnion and Ward, 1990], the high terrestrial erosion rate has left only a few craters preserved enough to allow testing various models involving atmospheric effects. The cratering record revealed by Arecibo [Campbell et al., 1990] and Venus [Basilevsky et al., 1987; Ivanov et al., 1986] provided important clues and enigmas, but the remarkable details revealed by Magellan images [Phillips et al., 1991] establish a template not only for recognizing the diversity in interactions between the impact process and an atmosphere but also for calculating energy partitioning and testing crater scaling relations, essential for calibrating geochronologies. An impactor entering the atmosphere of Venus partitions a portion of its original kinetic energy (KE) directly to the atmosphere prior to impacting the surface with KE (see Figure 1). For a Tunguska-like event the impactor catastrophically disrupts the surface and essentially all of the energy is partitioned to the atmosphere. Surface features suggestive of this process were first identified in the early Magellan analysis [Phillips et al., 1991], and the limit of surface effects from such a blast might provide a means to constrain KE.

At impact, energy is partitioned to the atmosphere indirectly from high-speed ejecta, expanding impact-induced vapor, frictional drag, and turbulence/winds induced by the outward moving wall of ejecta. Such a distinction between direct and indirect partitioning may seem trivial at first but is essential in order to emphasize that most of the kinetic energy for large impactors is first coupled to the target (in contrast with an above-surface, stationary nuclear explosion). This separation between early time (during the compression stage) and late time (during the excavation stage) atmospheric response explicitly acknowledges that surface signatures created by both the early time high-speed ejecta and expanding impact vapor cloud (blast effects) could be very different from the late time atmospheric response (winds and turbulence) caused by the ejecta curtain moving through the atmosphere, even though a large fraction of the initial kinetic energy of the impactor is ultimately deposited in the atmosphere. Energy partitioned to the impactor (~50%) is typically lost under vacuum conditions. But in a dense atmosphere, kinetic (high-speed vapor/melt) and internal (thermal energy of expansion) energy is transferred to the atmosphere at early times. At low impact angles (<30ø), kinetic energy retained by the impactor increases [Gault and Wedekind, 1977; Schultz and Gault, 1990]. Consequently, energy coupled to the atmosphere at early times can arise not only from an expanding vapor cloud and hypersonic ejecta but also from the rapid deceleration of ricocheted projectile. Figure 1 then provides a basis for characterizing key processes to be identified around selected craters.

Other studies in this special section emphasize statistical aspects of the Venus cratering record and possible implications, i.e., an inductive mode of investigation. The following study emphasizes the alternative deductive mode whereby various models of crater formation and atmospheric interactions are tested against the cratering record. These models have evolved from comparisons of processes inferred from laboratory impact experiments with craters in different environmental settings (atmosphere, gravity). Consequently, the approach will be to consider three basic questions. First, what is the response of the impactor to the thick Venus
Phillips et al. [1991] provides a basis for calculating the possible effects of direct coupling of impactor energy to the target prior to reaching the surface, thereby resulting in Revelstoke-systematic progression of crater "extinction" described by Krinov, 1966. The specific criteria for catastrophic style failure during entry are beyond the scope of this contribution. Rather, the focus will be on the effects of the atmosphere on cratering processes that indirectly transfer impactor energy to the atmosphere and for considering the expected signatures on the surface.

An object passing through an atmosphere to an altitude \( h \) will decelerate from \( v_o \) to \( v \) according to the following well-known formula for entry in an atmosphere with density decreasing exponentially with altitude:

\[
\ln\left(\frac{v}{v_o}\right) = -\frac{1}{2} \frac{C_D \rho_o A H_o}{M \sin \theta} \cdot e^{-h/H_o}
\]

(1a)

\[
\ln\left(\frac{v}{v_o}\right) = -\frac{2}{8} \frac{C_D \rho_o A H_o}{\delta \sin \theta}
\]

(1b)

\[
\frac{\Delta K E}{K E_o} = 1 - \left(\frac{v}{v_o}\right)^2
\]

(1c)

This formulation ignores energy losses by heating and ablation but provides a first-order estimate that closely matches numerical computations, provided that successive failure and dispersal does not occur [Baldwin and Schaeffer, 1971; Melosh, 1981]. For illustration, equation (1) predicts that a 2-km-diameter asteroid (8 \( \approx \) 2.8 g/cm\(^3\)) would deposit about 36% of its energy (20% reduction in velocity) during a 45\(^\circ\) entry for \( C_D = 0.8 \), while a 2-km-diameter comet (8 \( \approx \) 0.5 g/cm\(^3\)) would deposit about 48% of its energy (72% reduction in velocity) for \( C_D = 0.8 \) and \( H_o = 15 \) km.

The maximum deceleration experienced by a single body entering an atmosphere can be calculated from the derivative of equation (1a) and occurs when its velocity \( v \) has reduced to about 61% (i.e., \( e^{-1/2} \)) of its initial entrance value \( v_o \).

\[
\frac{dv}{dt} = -\frac{v^2 \sin \theta}{H_o} \ln\left(\frac{v}{v_o}\right)
\]

(1d)

\[
\left(\frac{dv}{dt}\right)_{\text{max}} = -\frac{v_o^2 \sin \theta}{2eH_o}
\]

(1e)

If the body survives this maximum stress, then it will be gradually decelerated to terminal velocity. Larger objects, however, never achieve this maximum possible deceleration. Rather, they either fail catastrophically or impact the surface. Hence the greatest possible decrease in the impactor kinetic energy prior to catastrophic failure leading to an above-surface burst will be about 37% of its initial value, i.e., (0.61)\(^2\). Equation (1d) reveals that the rate of increase in aerodynamic stress decreases with decreasing entry angle. Since catastrophic disruption should depend on the rate of applied stress, objects with low entry angles should have a greater probability of survival to lower altitudes.

The surface of Venus should be affected by two processes associated with impactors failing to reach the surface. Catastrophic failure above the surface creates a strong shock resembling an above-surface explosion at sufficiently large distances. The resulting air blast impinging on the surface dislodges material due to the large peak dynamic pressures in the shock front and the trailing rarefaction. Turbulence and recovery winds created by pressure and thermal gradients in the atmosphere then entrain and suspend finer fractions. Analogy with an above-surface explosion, however, applies only at large distances. Close to the impactor during entry, however, the transfer of kinetic to internal energy does not resemble a...
stationary point source. Rather, it forms a cylindrically expanding shock [Schultz and Gault, 1979; Ivanov et al., 1986] and may retain significant momentum from the impactor as well [Schultz, 1992a]. Effects from the distant air blast and near-impactor processes should produce distinct surface signatures. These two processes and their expected consequences are considered in more detail below.

Catastrophic failure creates an atmospheric shock that expands spherically with time at large enough distances away and can be described to first order by the classical blast wave solution [Taylor, 1951]:

\[ R_s = 0.9 \left( \frac{E_A}{\rho} \right)^{1/3} \nu_A^{2/3} \]  

(2)

where \( E_A \) is the energy (cgs) coupled to the atmosphere, \( \rho \) is the ambient density, and \( T \) is the time when the shock front reaches a radius \( R_s \) from the source. Surface effects from the atmospheric shock should reflect three different responses: surface disruption from the air blast-induced ground shock, strong winds created by pressure gradients once the shock has dissipated, and turbulence and winds in response to thermal gradients once atmospheric pressure has equilibrated.

When the pressure jump in the shock front drops to ambient values, the shock front has achieved a radius \( R_B \) in a time \( T_B \) characterizing the air blast stage:

\[ R_B = 0.5 \left( \frac{E_A}{\rho} \right)^{1/3} \nu_A^{2/3} \]  

(3a)

\[ T_B = 0.18 \left( \frac{E_A}{\rho} \right)^{1/3} \nu_A^{3/3} \]  

(3b)

where \( \nu_A \) is the velocity limit of the blast front, nominally taken as the speed of sound \( c \), and units are in cgs. The radius can be expressed in terms of the impactor kinetic energy with velocity \( v_i \), density \( \delta \), and radius \( r_p \):

\[ R_B/r_p = (3.4 \times 10^{-3}) (\delta/\rho)^{1/3} (v_i^{2/3} v_A^{2/3}) \]  

(3c)

where \( k \) is a coupling factor representing the fraction of the preentry kinetic energy transferred to the atmosphere. The minimum value of \( k \) for Tunguska-like burst will be about 37% corresponding to the greatest decrease in impactor velocity before reaching the maximum stress, that is, \( v_1 = 0.61 v_o \).

Equation (3c) can also be used for blast waves created by an impact where \( k \) now represents the fraction of \( \Delta E_p + \Delta E_i +KE_p +KE_i \) coupled to an early time shock (subscripts \( p \) and \( t \) indicate projectile and target contribution, respectively).

Even after the shock front has decayed to a sonic wave, conditions behind it have not [Taylor, 1951]. Atmospheric pressure equilibrates to ambient conditions after the disturbance has grown to \( R_E \) in a time \( T_E \):  

\[ R_E = (4.2 \times 10^{-3}) E_i^{1/3} \]  

(4a)

\[ T_E = (1.5 \times 10^{-6}) E_i^{1/3} \rho_i^{1/2} \]  

(4b)

In contrast with the blast limit radius given by equation (3a), the radius of the disturbed atmosphere scaled to the impactor radius does not depend on atmospheric density:

\[ R_B/r_p = (6.77 \times 10^{-3}) (\delta/\rho)^{1/3} v_i^{2/3} \]  

(4c)

From equations (3) and (4), the atmospheric disturbance grows to 10 times larger than the limit of the air blast before the ambient pressure returns (for conditions at surface) and takes at least 30 times longer.

Surface effects from a strong air blast should reflect different responses of the disturbed atmosphere over time. First, passage of the shock front creates a large overpressure on the surface, immediately followed by a rarefaction. The resulting “air blast-induced ground shock” is a well-studied phenomenon [Cooper, 1977]. On Venus, the maximum density in the shock front is given by

\[ \rho_s = \rho_i (y + 1)/(y - 1) \]  

(5)

Consequently, the impinging shock for Venus would have a density approaching water, as previously emphasized by Ivanov et al. [1986]. Directly below the region of catastrophic failure, the shock front parallels the surface and exerts a large overpressure [Phillips et al., 1991]. At large distances, the shock strikes obliquely and dislodges surface debris, while the pressure differential in the trailing rarefaction draws material in a rolling vortex as observed in laboratory experiments and around large explosions. The air blast lasts until the shock front has reduced to near sonic velocities (equation (3b)).

Closer to ground zero, atmospheric pressures have not equilibrated (equation (4)), and this pressure differential creates an inward directed recovery wind with entrained debris. Energy deposited in the atmosphere closer to the “source” results in a fireball". Consequently, surface expression from a strong air blast should exhibit not only disruption (roughening) but also later redistribution due to recovery winds.

The limit of air blast effects scaled to impactor size from equation (3c) is shown in Figure 2 for different planetary atmospheric environments and typical impact velocities. On Mars the blast zone should extend hundreds of projectile diameters [see Schultz, 1988a]. Since the tenuous atmosphere on Mars allows all but impactors less than about 5-10 m to survive entry, blast effects from a Tunguska-like should be limited to 10-20 m. On Venus, however, the dense atmosphere restricts the blast zone to a much smaller area (Figure 2).

![Fig. 2. Limit of atmospheric blast (front advancing greater than the speed of sound) scaled to projectile diameter under different planetary atmospheres. The expansion limit is shown for different levels of energy partitioned to the vapor cloud expressed as percentage of the original impactor energy. On Mars, the cloud expands well beyond the crater, whereas on Venus the dense atmosphere contains the cloud within several projectile radii. These results are likely lower limits for an expanding vapor cloud, which does not resemble a point source except at large distances.](image-url)
A first-order comparison can be made between the limit of atmospheric response and crater size. If the crater had formed in a vacuum, crater scaling relations for wet sand (nonporous) suggested by Schmidt and Housen [1987] provide the following:

\[
R_c = 0.70(KE)^{0.26}g^{-0.09}v^{-0.22} \\
T_c = 0.63(KE)^{0.15}v^{-0.04}g^{-0.61}
\]

where \(R_c\) is the apparent crater radius, \(T_c\) is the time for crater excavation, and \(g\) is the gravitational acceleration all in egs units. Figure 3 allows comparing the maximum dimensions of the atmospheric blast limit and crater size. It is fully recognized that considerable uncertainty remains in scaling relations extended to large scales; nevertheless, equation (6) and Figure 3 provide a useful reference. A Tunguska-like atmospheric blast without formation of an impact crater on Venus provides a means to recognize the blast signature around larger events surviving entry to form craters. Moreover, comparison of air blast signatures with and without a crater provides a means to estimate the limiting size of the impactor and to calibrate the coupling factor \(k\).

The preceding discussion focused on possible effects far from the region where the impactor transfers its energy to the atmosphere. Although smaller meteors entering the terrestrial atmosphere are observed to disrupt in an explosive release of energy, larger bolides typically disrupt in stages [see Baldwin and Schaeffer, 1971]. Consequently, objects surviving entry to the surface may produce distinctive interactions and effects. Laboratory experiments allow examining this complex process and produce unexpected results.

Catastrophic failure of the impactor is simulated by placing a thin sheet of paper or aluminum in its path [Schultz and Gault, 1985a]. As the projectile passes through the paper at hypervelocities, the induced shock in the projectile causes catastrophic disruption without significantly reducing the original velocity. Experiments with witness plates placed at the target surface recorded the dispersion pattern of the impacted fragments (Figure 4). Under vacuum conditions, the debris cloud formed by disrupted pyrex spheres creates a well-defined pattern of large and small impacts as shown in Figure 4a. In an atmosphere, this dispersion increases with atmospheric pressure (density) up to about 0.25 bars (Figures 4b and 4c) as interacting bow shocks create lateral spreading forces [see Melosh, 1981]. Smaller fragments appear to be filtered out through differential drag, but Figure 4c also reveals that a densely packed halo of much smaller impacts surround each large pit. Such a pattern reflects the role of the bow shock in forming a shield behind which wake gases travel with the largest mass fragment. Smaller fragments entrained in the wake experience significantly reduced aerodynamic drag.

In contrast with expectations and predictions, however, dispersal did not continue to increase at higher atmospheric pressures. As shown in Figure 4d, a single hole was produced at a 1-bar atmosphere. Use of an aluminum block (instead of a thin witness plate) as a target produced a crater as if the projectile had not fragmented and as if there were no atmosphere.

High frame rate photography (25,000 frames per second) allowed comparing the reduction in velocity for the debris cloud and an unbroken projectile (Figure 5a). Aerodynamic drag forces decrease the velocity of a projectile from \(v_o\) to \(v\) over a distance \(L\) according to the following relation:

\[
\ln(\frac{v}{v_o}) = -12CD\frac{A}{L}m_p\rho_o
\]

where \(CD\) is the drag coefficient, \(\rho_o\) is the ambient density, and \(A\) is the cross-sectional area of the projectile with mass \(m_p\). Figure 5a reveals that the cluster decelerated as if the 0.635 cm sphere had not disrupted, whereas fragments isolated from this tight cluster (and producing the outlying impacts in Figure 5b) underwent considerable drag deceleration consistent with fragment sizes less than 0.05 cm across.

The unexpected results from Figures 4 and 5 indicate that the bow shock at higher densities helps to contain rather than disperse the fragments. At the high velocities (3-5 km/s), the mass cone becomes so acute that it is better described as a mach column. Moreover, the high-speed film record reveals that the debris cloud deforms into a needle shape that minimizes the drag coefficient, thereby reducing deceleration. These experiments suggest that atmospheric breakup actually may assist surviving atmospheric entry to the lower atmosphere. Asteroids with thick regoliths or evolved comets should be particularly good survivors.

Under vacuum conditions, the hypervelocity debris clouds impacting particulate targets (sand and pumice) created shallow craters, consistent with energy transferred near the surface [Schultz and Gault, 1985a, b]. With increasing atmospheric pressure, craters produced by a dispersed cloud of pyrex fragments became smaller in diameter as atmospheric effects on excavation reduced cratering efficiency (Figure 6a). At 0.25 bars (nitrogen), the pyrex cloud formed only a shallow depression surrounded by radial scouring (Figure 6b). The scouring resulted from strong outward toroidal flow resembling flow from a stagnation point analogous to an impinging jet. Sintered and fused projectile fragments littered the surface, and fine-grained debris remained suspended in the atmosphere long after impact. Reflected shock and rarefaction waves from the chamber walls created pulsations in the ejecta cloud directly above the impact point. In contrast, the aluminum debris cloud at higher pressure (1 bar of argon) created a central crater, strong toroidal ejecta flow, and peripheral small pits from decelerated smaller fragments (Figure 5b).

The experimental results in Figure 6 reveal that considerable momentum may accompany disrupted impactors. Allowing the projectile to pass through an opening in a solid plate covered with a thin layer of sand reveals just the effects of wake blast. As described in more detail elsewhere [Schultz, 1992a, c], the impinging wake (vertical collision) beyond four projectile radii from the trajectory axis created a scour zone that depended...
Fig. 4. Effect of atmospheric density on dispersion of a supersonic debris cloud (3–5 km/s). A pyrex sphere is disrupted by passage through a thin sheet of paper and produces the tight pattern in aluminum witness plates shown in Figure 4a as described by Schultz and Gault [1985a. Under 0.125 bars of argon (Figure 4b), smaller fragments are dispersed, but under 0.25 bars of argon (Figure 4c), smaller fragments become clustered around the five largest members. At 1 bar with argon (Figure 4d), the entire cluster forms a collimated debris stream that forms a single hole. While interfragment distances begin to increase with increasing density as expected theoretically [Melosh, 1981], fragments fail to disperse at high densities [after Schultz and Gault, 1992].

on atmospheric composition (sound speed $c$ and ratio of specific heats $\gamma$):

\[
\left( \frac{r_b}{r_p} \right)^2 = \left( \frac{3 \times 10^5 P \gamma M^2}{\delta_i c^2} \right)
\]

or

\[
\frac{r_b}{r_p} = \left( \frac{548}{\delta c^2} \right)^{1/2}
\]

where $r_b$ is the observed scour limit scaled to the impactor radius $r_p$, $P$ is the atmospheric pressure, $v_i$ is the wake collision velocity, and $\delta_i$ is the bulk sand density with all units in cgs. For a compressible gas at hypervelocities, the stagnation pressure $P\gamma M^2$ should be replaced by $PM^2(\gamma - 1)$. The scour limit described by equation (8) exceeds the blast limit from equation (3c) by a factor of 3 (for $k = 0.1$) because it involves lateral movement (saltation) by outward winds considerably lower than the speed of sound.

The scour zone from the projectileless impacts results from the hypervelocity collision of wake gases trailing the
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solid sphere disrupted sphere

expected value (0.635cm)

isolated fragments

expected value (470µ)

Fig. 5a. Comparison of observed deceleration of intact and disrupted aluminum fragments traveling at hypervelocity (5 km/s) through an atmosphere (0.9 bar of argon). Measurements were made from high frame rate (25,000 frames per second) photographs. Intact aluminum impactor follows expected velocity decrease. Disrupted impactor cloud, however, exhibits essentially the same deceleration even though it is comprised of numerous small (< 0.01 cm) fragments. Observed fragments isolated from the cloud, however, undergo the anticipated deceleration. This result suggests that the impactor cloud deforms into a shape that minimizes drag and/or creates a bow shock as if it were a large solid object, as confirmed in photographs. Pyrex debris clouds produce identical results.

These experiments provide insight for the survival, shape, and expected surface signatures of objects near the disruption limit (onset size of catastrophic disruption) during atmospheric entry on Venus since the basic physical processes should not change. First, they reveal that analogy with a stationary atmospheric explosion above the surface is an end-member from a range of effects. An impinging hypervelocity cloud creates outward flow from a stagnation point along the trajectory axis with outward scouring off axis. Recovery winds from this collision redistribute finer suspended material. Second, trailing meteoritic debris and ablation products may subsequently be deposited on the surface. Third, perhaps not all impactors surviving entry deform into a flattened shape as described by Melosh [1981]. The laboratory experiments reveal that a disrupted or fragmented body also will deform into a shape providing the least dynamic resistance. On Venus, this process may allow objects smaller than the disruption limit to reach the surface. Moreover, the resulting craters could take on unusual profiles. And finally, partial failure of larger impactors should be trailed by much smaller debris with only slightly reduced velocities due to the shadowing effect. Tests for these phenomena include evidence for the following observations: outward directed blast effects and redistributed finer-grained material around craterless blast centers; unexpectedly small craters or crater clusters associated with such craters or larger

Fig. 5b. Pattern produced by hypervelocity (5 km/s) impact of aluminum cluster (Figure 5a) into a pumice target at a 60° angle from the horizontal (arrow shows impact direction). The small central crater is consistent with aerodynamic reshaping and containment of the cluster. Impacts of solid aluminum blocks by aluminum or pyrex debris produce deeper craters.
craters; interference and redistribution of crater ejecta from the influx of trailing wake material.

In summary, the processes observed in the laboratory can be tested at much larger scales by comparisons with features near the limit of impactor disruption on Venus. If the impactor failed to reach the surface, then blast effects revealed by shock disruption and redistribution of entrained smaller debris should be visible. The outer limit of such a zone should provide a measure of the source energy and impactor dimensions (for an assumed entry velocity and impactor density). With increasing impactor size or strength, wake-wind effects or fallout and redistribution of impactor ablation products should be evident.

Fig. 6. Effect of atmospheric density on dispersed cloud of hypervelocity pyrex fragments. Figure 6a shows the small, shallow crater produced under a 0.059-bar (nitrogen) atmosphere from a 6.1 km/s impact. At higher atmospheric pressures (0.26 bar, nitrogen) in Figure 6b, the dispersed cloud creates a central stagnation zone with intense outward scouring (impact velocity of 5.9 km/s) indicated by radial pattern.

Fig. 7. Atmospheric effects created by collision of the projectile wake decoupled from the projectile for a 45° trajectory. The target is an aluminum plate covered by a thin layer of no. 24 sand with small styrofoam balls as tracers (Figure 7a). The limit of the scour zone for vertical collisions increases as \( P^{1/2} \alpha^{1/2} \) for an atmospheric pressure \( P \), ratio of specific heats \( \gamma \), grain density \( \rho_0 \), and atmospheric sound speed \( c \) as discussed by Schultz [1992a]. Uprange the styrofoam tracers were driven into the sand veneer before being blown away, whereas downrange they were lofted with little trace (Figure 7b). The scour pattern reveals uprange removal of sand related to impingement by the outward expanding cylindrical shock created by the projectile as suggested by Ivanov et al. [1986]. Downrange, however, the colliding wake scours a path. Transverse dunes (perpendicular to the impact trajectory) were also created uprange in response to afterwinds drawn downrange behind this wake (Figure 7c). Hence the impactor wake contains considerable dynamic pressure reflecting its own velocity, even if decoupled from the projectile. On Venus, a similar “memory” of the impactor dynamic pressure should be expected for bodies disrupting just above the surface. Moreover, afterwinds should create dunelike patterns.
Cometary and asteroidal impactors at such scales could have very different signatures since the ablation products (and their expected within the wake-disturbed zone. As crater size increases, however, atmospheric blast effects should decrease as energy is coupled first with the target and may be affected by interaction with the early time ejecta plume. Nevertheless, the power within the trailing wake should be in evidence, particularly for oblique impacts.

Direct Energy Transfer Signatures on Venus

Craterless blast haloes. The first analyses of Magellan images noted the progressive "extinction" of craters associated with dark margins [Phillips et al., 1991]. Since that report, broader coverage of Venus reveals that there appears to be a sequence (Figure 8) from diffuse radar-bright splotches (BH) to radar-dark surrounded by a radar-bright halo (DBH) to a radar-bright halo surrounding a radar-dark splotch containing a central radar-bright crater cluster (CBH), and last to a central crater cluster surrounded by a dark thin diffuse bright halo (CDH). Preimpact features including low-relief wrinkle ridges and fractures commonly become ill-defined within the bright halo. A closer look reveals that the more prominent structures remain visible even through the center (Figure 9a). An equally important clue for interpretation is the systematic occurrence of radar-dark materials on one side of a ridge or filling in fractures (independent of look angle). The radar-dark materials in Figure 9a occur along the base of ridge scarps facing the center of the halo. Considerable variation in expression can occur, however. Figure 9b shows a DBH feature with parallel bright streaks extending to the southwest and a complex array of dark lobes extending away from the center in a pseudo-butterfly pattern. Darker materials generally occur along ridge scarps facing southwest. In addition, there is muting of very narrow features to the northeast with the large fractures exhibiting darker materials on the northeast facing wall, thereby creating an impression that they have positive, rather than negative, relief.

The various features and patterns shown in Figures 8 and 9 are consistent with processes witnessed in laboratory experiments illustrated in Figures 4-6. The radar-bright haloes can be interpreted as scoured and roughened surfaces created by the passage of a strong, outward moving atmospheric shock and recovery winds. If the effective altitude of breakup approaches the lateral blast limit, the impinging shock will strike the surface more directly and will not be appreciably affected by topography (Figure 8a). It is suggested that radar brightening is not only in response to compression and decompression of surface materials [Phillips et al., 1991] but also reworking (mini-dunes) by response winds. When disruption occurs near the surface, the shock front at large distances strikes the surface obliquely but impinges more directly on high relief (hills, mounds, ridges). Radar brightening toward and darkening away from the blast source (roughening and blast shadowing, respectively) illustrated in Figure 8d are consistent with such a process.

The radar-dark material has two possible origins. First, atmospheric recovery to the shock for a more vertical impact creates a reversal in airflow, which draws entrained debris back toward the source in a manner very similar to both above-surface explosions on Earth and laboratory experiments. As this wind encounters positive relief, the debris should be deposited on the leeward side [see Greeley and Iversen, 1985]. Second, ablated debris associated with the impactor continues downward to the surface within the trailing wake, thereby interacting with the atmospheric shock. The radial streaks within the inner dark zone of Figure 9a and blockage by low relief are consistent with outward basal flow from a stagnation zone witnessed in laboratory experiments (Figure 6b) rather than smoothing by strong overpressures. As debris entrained in the wake collides with recovery winds or a reflected shock from the surface, however, a standoff shock should form. This provides a possible explanation for the dark ring commonly observed within DBH features (e.g., Figure 8b).

The oblique projectileless collision shown in Figure 7b provides a particularly striking analog for the pattern in Figure 9b for an impactor approaching from the southwest. The bright parallel streaks extending to the southeast most likely reflect surface scouring associated with the cylindrically expanding wake column, as recorded in the paths of the styrofoam tracers in Figure 7b. The principal difference between the experiments and the proposed analogs on Venus is the downrange scouring caused by continued momentum in the wake. The dense atmosphere of Venus very likely will result in a standoff (dark lane to the northeast) or diffusion through turbulence unless the impactor ricochets (skips) off the lower atmosphere.

Wake blast effects. Direct evidence for the dynamic pressure and deposits produced by the trailing wake on Venus can be seen in Figure 10. The crater cluster in Figure 10a occurs in the ridged and fractured plains near 9°N, 358°E. The butterfly pattern characterizing highly oblique impacts, however, is different from those produced in the laboratory by single, solid impactors [Gault and Wedekind, 1978; Moore, 1979]. First, the ejecta butterfly more resembles a "fly": the "wings" are not perpendicular to the trajectory axis but form a V-shape pointing uprange. A similar pattern has been produced by double impacts under vacuum conditions in which the uprange crater forms first [Oberbeck and Morrison, 1974]; it also has been produced by oblique clustered impacts [Schultz and Gault, 1985a]. Second, the "wing tips" of the distal ejecta lobes extend downrange, parallel to the trajectory. This is not a pattern of ballistic emplacement but indicates entrainment and redistribution, consistent with wake phenomena observed in the laboratory without (Figure 7b) or with impact by the projectile [Schultz, 1992a]. Because virtually no ejecta are directed uprange, the radar-dark zone extending uprange must be directed directly to the wake. As in Figure 8, a "shadow" of radar-dark material occurs on downrange-facing scarps, consistent with wake-induced winds depositing material on the lee side. A more subtle splitting of this radar-dark uprange "runway" occurs downrange and suggests interference and divergence of winds driven by the wake. Farther downrange the radar-dark material becomes mottled.

Figure 10b illustrates a pair of oblique impacts. The larger member (16 x 14 km) exhibits a well-preserved butterfly to the north but is poorly expressed to the south where a smaller (8 x 7 km) companion impacted downrange. The brighter ejecta component exhibits the same curved ejecta "wings," suggestive of interference with an impinging wake. Additionally, ejecta from the larger companion has been clearly muted, if not partly removed, by interference with this wake.

Processes associated with air blast from atmospheric breakup and wake blast are summarized in Figure 11a. During entry, objects deposit most of their energy in an atmospheric layer of constant thickness Δh (about 25 km), regardless of altitude or velocity [e.g., Gazley, 1958; Schultz and Gault, 1982]. If the object undergoes catastrophic disruption, then this layer or zone reduces dramatically. The altitude h at which maximum deceleration occurs (maximum energy transferred to the atmosphere) however, does depend on object size (radius r) and density δ and is given in terms of the atmospheric scale height by:

$$h/H = \ln(0.75C_d p_0 H_0 r / \delta \sin \theta)$$  (9a)
Fig. 8. Progression from radar-bright haloes without craters (BH, Figure 8a) to bright haloes surrounding radar-dark zone (DBH, Figure 8b) to bright haloes surrounding a dark central zone with small central pits (CBH, Figure 8c) to craters surrounded by a diffuse dark halo and faint bright halo (CDH, Figure 8d). Bright-haloed zones without craters commonly contain spiderlike pattern of darker materials resembling flow from a stagnation point in the laboratory (Figure 6b). Surface features are muted but visible in the radar-bright zone and are believed to indicate disruption of the surface by the intense atmospheric shock and rarefaction. Dark materials typically occur on the facing side of the low-relief wrinkle ridges suggestive of deposition during basal flow. These deposits may represent ablation remnants of the impactor entrained in the impinging wake after disruption (as in Figure 5). Dark ring may represent a standoff zone created as outward flow from impactor remnants collide with inward flow (following rarefaction) after atmospheric equilibration. Radar-brightened hills and streaks facing the source (white arrows, Figure 8d) as well as the radar-dark region away from the source in Figure 8d (dark arrows) indicate the effects of the full force of the blast on exposed relief (landslides and effects of reverse winds) and shadowing, respectively. Most radar-bright haloes are symmetrical, most likely indicating both the intensity of the above-surface blast and loss of information about the source geometry at great distances. As impactor survival allows formation of a crater, energy directly coupled to the atmosphere decreases and the bright blast halo becomes proportionally smaller (Figure 8d). Figure 8a is at -12.5°S, 356.5°; 8b at 37°N, 5°; 8c at 48°N, 350°; and 8d at 42.5°N, 349.5°. Bar scale in Figure 8a corresponds to 50 km (applies to other images as well).
Fig. 9. Effect of surface relief in disruption of radar-dark deposits. Asymmetry in pattern in Figure 9a is created by a low-relief fracture that disrupts and induces turbulence in the outward flow creating the radar-dark deposits (arrow). Figure 9b shows an asymmetric radar-dark butterfly pattern comprised of dark patches typically concentrated on one side of wrinkle ridges (arrows). It is suggested that this pattern was produced by an oblique collision with remnants of the impactor and its wake, analogous to Figure 7b. In the case of Venus, however, downrange scouring by the wake is prevented due to the dense atmosphere. The "runway" of parallel radar-bright lineations would be consistent with impingement by the cylindrical shock expanding from the impactor prior to impact as indicated by the downward-then-outward paths of styrofoam balls in laboratory experiments (Figure 7). Figure 9a is at 12°S, 267° (P-108267); Figure 9b is at 47°S, 136° (C1-45S138).
Fig. 10. Small craters formed by oblique impacts on Venus that demonstrate the potential dynamic pressure in the trailing impactor wake suggested from laboratory experiments (Figure 7). The example in Figure 10a exhibits a V-shaped “fly” pattern with downrange streamers from the “wing tips” in contrast with the butterfly pattern for impacts under vacuum conditions (largest crater is about 11 km long). The V-shape could reflect interference due to multiple impacts (see Schultz and Gault, 1985a) but the downrange streamers indicate redistribution of ejecta due to interactions with the trailing wake or draughting downrange caused by ricochet. Impacts are at 9.3°N, 357.8°. Figure 10b shows interference resulting in downrange curving of ejecta wings and disruption of ejecta deposits of adjacent crater. Wake blast from the approaching impactor can be identified uprange by a radar-bright zone perhaps indicating formation of minidunes or ripples and radar-dark deposits representing either impactor ablation products or winnowed finer-grained surface material from wake winds (solid white arrows). The larger crater is 16 km x 14 km; the smaller example is 8 km x 7 km.

Fig. 11a. Proposed scenario for the formation of radar-bright zones and dark deposits. Successive failure of the impactor during entry may result in reshaping of the debris cloud, thereby minimizing drag and allowing deep penetration as in laboratory experiments (Figure 4). When the density in the compressed air cap approaches the density of the impactor in the lower atmosphere on Venus, however, the compressive wave induces catastrophic disruption. The lower atmosphere essentially behaves as a solid target (left). For a comet with preentry density of 0.5 g/cm³, this condition would be met within an atmospheric scale height of the surface. Consequently, most radar-bright halos are symmetrical (even though most entry angles approach 45°); the distance r to which the blast remains as a shock is much greater than the height of disruption h and the zone over which energy is directly coupled Ah. The effect of the blast is not just to disrupt the surface but also to create strong recovery winds that rework material dislodged by the air blast-induced ground shock, perhaps into small dunes that appear rough at radar wavelengths. If the object is sufficiently large (or dense), then it may reach the surface where ablated and fragmented impactor materials within the trailing wake impinge on the surface (right). Outward flow from the stagnation zone creates scouring and strong winds as observed in laboratory experiments (Figures 6 and 7).

Fig. 11b. Source energy derived from the outer limit of observed radar-bright zone using equation (3) for bright-bolted areas containing dark deposits without (DBH) and with (CBH) identifiable craters. It is assumed that the radar-bright zone corresponds to surface roughening created by compaction/decompression of surface materials by the atmospheric blast wave. Source energy is derived for an atmospheric density at 20 km with the assumption that all of the impactor energy is transferred suddenly to the atmosphere (i.e., k = 1 in equation (3c)). Impactor size can be calculated if impactor density and velocity are assumed. Asteroidal values are assumed (ρ = 2.5 g/cm³ and v = 28 km/s); cometary values result in very similar estimates of impactor size since higher impactor velocity is offset by lower density. Use of a lower impact velocity results in large derived impactor sizes. It appears that the smallest impactor creating a blast that affects the surface is about 0.6-1.0 km in diameter. The largest impactor forming a craterless blast zone approaches 4 km in diameter in this analysis. This result is contradictory with the formation of much smaller craters (1-3 km in diameter) and may indicate different impactor types.
which yields the diameter \(2r_o\) of the largest object (given density) when the maximum energy deposition in the atmosphere occurs just above the surface.

\[
2r_o = 1.5C_p\rho H/\sin\theta \tag{9b}
\]

For a density of 2.8 g/cm\(^3\) and entry angle 45°, \(2r_o\) is about 0.9 km. A chondritic object no smaller than this size should reach the surface before depositing 50% of its energy into the atmosphere along a 25-km-long zone. Because dynamic pressures will greatly exceed its compressive strength well before reaching the surface, this result principally serves to establish a lower limit for reference. Moreover, the region \(\Delta h\) of maximum energy deposition must then be considered an upper limit. When \(R_g>\Delta h\), the assumption of an equivalent point source at large distances can be justified and is consistent with the overall symmetry of the radar-bright zones (Figure 8). Closer to the region of breakup, however, such an assumption is invalid.

Catastrophic disruption may occur lower in the atmosphere if the stress rate (as well as maximum stress) is decreased or delayed. This can occur for objects with lower entry angles (equation (1d)), and the experimental results shown in Figures 4 and 5 suggest an additional mechanism. An evolved short-period comet (a devolatized rubble pile) with a 30° entry angle may minimize its drag coefficient by changing shape during its 10 second transit time. As the lower atmosphere is reached, however, the rate of stress build-up should offset the rate of decrease in the drag coefficient leading to rapid compression and sudden breakup. Such a scenario will be explored further in future calculations and experiments, but can be supported qualitatively by extraordinarily long dark streaks extending to (and from) small craters on Venus (Figure 10). Consequently, the altitude of catastrophic breakup may depend on the physical nature of the object and entry angle as well as total dynamic stress.

If the radar-bright haloes represent the effect of surface disruption by an atmospheric blast, then their outer boundary should provide an indication of the energy fraction coupled to the atmosphere where details of the partitioning process are lost. Figure 2 (equation (2c)) then provides an indication of impactor size. The fraction of the impactor energy coupled to the atmosphere should change, as objects successfully survive passage through the atmosphere and directly partition more energy to the target instead of the atmosphere. For the examples in Figure 8, the limit of surface disruption should increase from BH to DBH to CBH features. Figure 11b tests this suggestion. Figure 11b reveals that the radar-bright haloes containing radar-dark deposits generally are larger than 10 km in radius, but smaller than about 60 km. The corresponding minimum energy resulting in a 10-km-radius bright halo yields a 0.4-km-radius projectile (density of 2.5 g/cm\(^3\) and velocity of 28 km/s) and is termed the "blast limit". Smaller objects cannot penetrate deeply enough into the atmosphere of Venus to produce a radar-brightened surface.

Radar-bright haloes containing one or more small craters typically are larger than 60 km in radius, a blast limit corresponding to a body originally as large as 4 km in diameter. A smaller impactor size can be derived if it catastrophically disrupts above the surface: 60-km-radius halo corresponds to a 2.3-km-radius impactor disrupting at an altitude of 50 km, thereby producing a blast that would be close to supersonic by the time it reached the surface. This, however, must be considered a lower limit.

Larger size bodies are more likely to survive entry and directly transfer most of its energy to the surface, rather than directly to the atmosphere. The resulting halo size should then decrease as \(k\) decreases, even though the initial impactor kinetic energy is clearly greater. This will be documented further in the following section.

The response of the atmosphere to impactor energy provides a unique opportunity to calibrate scaling relations. The limiting impactor diameter surviving entry inferred from Figure 11b can be compared with the corresponding crater size predicted from equation (5a) as shown in Table 1. The derived crater diameters are a factor of 10 to 20 larger than the smallest single crater (not part of a cluster) on Venus as cited by Phillips et al. [1991]. The disparity could reflect an order-of-magnitude overestimate in cratering efficiency (the basis for equation (5)), an overestimate of the derived energy from the surface record (that is, equation (2) and Figure 11b), or a reduction in cratering efficiency due to the atmosphere. Alternatively, comets are principally responsible for the largest air blasts, whereas asteroids are responsible for craters down to the blast limit (Table 1). In this case, lower entry angles should favor larger (and weaker) objects reaching the lower atmosphere before catastrophic disruption by decreasing both the peak stress and rate of stress build-up as inferred from equation (1).

Features associated with the impact cluster in Figure 12 highlight the various processes suggested to be associated with direct energy coupling between impactor entry and the atmosphere. The effect of a strong atmospheric shock can be inferred from the erasure (or masking) of identifiable preimpact relief (ridges and fractures) around the two adjacent impact craters, 20 km and 11 km in diameter. To the south and southwest are two dark patches with bright haloes. A dark ring

<table>
<thead>
<tr>
<th>Altitude</th>
<th>(R_g) (^a) km</th>
<th>Impactor Diameter (^b) km</th>
<th>Crater Diameter (^c) km</th>
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<td>Blast Limit</td>
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<td>4.1</td>
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<tr>
<td>Cratering Limit</td>
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<td>1.2</td>
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<tr>
<td>(h = 20) km</td>
<td>12</td>
<td>0.87</td>
<td>0.94</td>
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\(^a\) From Figure 11b corresponding to largest radar-bright halo without a crater.
\(^b\) Based on equation (3c) for asteroids (\(S = 2.5\) g/cm\(^2\) and \(v_o = 28\) km/s) and comets (\(S = 0.5\) g/cm\(^2\) with \(v_o = 55\) km/s).
\(^c\) Based on equation (6a) with assumed values in the first footnote and corresponding impactor diameter. Crater diameter represents estimated rim-to-rim diameter (25% increase from apparent diameter and a 25% increase for enlargement by slumping). If impact velocity is reduced to 60% of its entry velocity (when maximum deceleration occurs), then the cited crater diameters would be reduced only about 15%.
is well developed toward the crater pair but is missing to the southwest. A similar but more subtle pattern occurs with the interference shocks. Radar-dark material filling the floors of narrow (<300 m wide) fractures enhance the extensional grain. Energy among target and projectile kinetic and internal energy.

Additionally, a diffuse radar-dark patch superposes ejecta lobes, but careful inspection reveals that the ejecta deposits are peppered with a myriad of very small (<200 m) craters. The limit of the crater field. Limit of radar-bright haloes with 100% (k = 1) atmospheric coupling result in derived impactor sizes (from Figure 11b) larger than sizes responsible for adjacent craters as discussed in the text. Radar-dark materials collect inside narrow fractures creating dark linearions crossing the radar-bright zones. Figure 12 shows the crater field and small nearby craters. It is suggested that the smaller craters are not secondaries but companion fragments surviving entry due to shielding within the wake of larger fragments responsible for the major craters (see Figure 4b and 5b). F-MIDR-35S163 (craters at 32.5', 163').

In summary, catastrophic disruption of impactors entering the atmosphere produces a distinctive signature on the surface due to passage of the shock blast and subsequent airflow. This process can be viewed as an atmospheric impact, i.e., the atmosphere as the target. The remarkable symmetry of most larger radar-bright haloes is consistent with energy release resembling a point source at large distances. The limit of the atmospheric response to a sudden point source release at large distances has been extensively studied in theory [e.g. Taylor, 1951; Zel'dovich and Razier, 1967; Jones and Kodis, 1982] and tested through observations of nuclear explosions [Taylor, 1951] and experiments in the laboratory [Schultz, 1988a; Schultz and Gault, 1990a]. The maximum size of the craterless blast zone on the surface provides a measure of the limiting impactor size capable of surviving entry. The minimum size crater not part of a cluster provides a minimum size of the impactor through existing scaling relations. These two limiting sizes, however, give contradictory results: blast-derived impactor sizes are consistently a factor 2-3 larger than crater-derived impactor sizes. It does not appear possible to reconcile this difference by simply assuming different impactor density since lower impactor density cometary objects typically have higher impact velocities. Perhaps the largest craterless blast haloes reflect large cometary objects that essentially "impact" the dense, lower atmosphere, whereas smaller craters (10-30 km) result from disrupted asteroids that survive entry in a collimated mach stream as observed in laboratory experiments.

Figure 12 illustrates the emplacement of craters and craterless haloes believed to indicate nearly simultaneous impacts and associated surface blasts from fragments not surviving entry. Figure 12a provides an overview, whereas Figure 12b permits a closer view of the crater field. Limit of radar-bright haloes with 100% (k = 1) atmospheric coupling result in derived impactor sizes (from Figure 11b) larger than sizes responsible for adjacent craters as discussed in the text. Radar-dark materials collect inside narrow fractures creating dark linearions crossing the radar-bright zones. Figure 12b shows the crater field and small nearby craters. It is suggested that the smaller craters are not secondaries but companion fragments surviving entry due to shielding within the wake of larger fragments responsible for the major craters (see Figure 4b and 5b). F-MIDR-35S163 (craters at 32.5', 163').
only slightly reduced from the initial impact velocity. As a result, oblique impacts (30°) in an atmosphere produce a visible airshock that is centered downrange from the crater in laboratory experiments. Features associated with craters on the Moon and Mars at much larger scale suggest that this process is not restricted, however, to laboratory scale events [Gault and Wedekind, 1978; Schultz and Gault, 1990a]. As impact velocities increase, the impactor penetrates farther into the target before the shock wave reaches the back surface of the projectile; consequently, the effects of decapitation might become less important or less evident [Schultz and Gault, 1990a].

On Venus, impactor decapitation could begin above the surface, thereby decoupling the ricochet complex from later stages of crater growth. The compressed air cap in front of an impactor on Venus achieves a maximum density approaching water (0.5 - 0.9 gm/cm²) as given by equation (5). Although the thickness of this compressed gas remains a relatively small fraction of the impactor (10%), it creates an interface between the projectile and target that can be viewed as either an effective increase in the projectile radius [Schultz, 1992a] or a pseudo-surface above the actual surface when a compressive shock begins to propagate back through the solid projectile. Oblique impacts (15°) into thin water targets (equal to a projectile radius) by pyrex and aluminum spheres at 5 km/s in the laboratory result in catastrophic failure of the projectile. The water targets were suspended in a tray of thin mylar which alone does not significantly alter the impactor trajectory. None of the ricocheted fragments impacted the downrange witness plates below the original target surface [Schultz and Gault, 1990b]. Consequently, the thin water target was sufficient to disrupt and deflect the hypervelocity projectile as if the target

![Fig. 13. Comparison of vapor cloud expansion and downrange ricochet for oblique impacts into dry ice (15° from horizontal) without (Figure 13a) and with (Figure 13b) an atmosphere (1 bar, argon); sequence shows time from impact in 57-μs intervals from bottom to top. (a) Without an atmosphere the vapor cloud expands and moves rapidly downrange. (b) Presence of an atmosphere severely limits vapor cloud expansion, but conditions are insufficient to rapidly decelerate downrange ricochet component. The early time high-speed jetting phase observed under vacuum conditions is entrained in the downrange moving vapor cloud. Under high atmospheric pressures, a reverse uprange jet is formed at about double the entrance angle. White dot indicates impact point (excepting bottom frame in each sequence). (c) Consequence of impact-induced vaporization on a crater formed in an easily volatilized powdered carbonate target in a vacuum is shown in Figure 13c. Under vacuum conditions, an oblique impact (15°) produces a luminous vapor cloud that expands very similarly to the example in Figure 13a. The resulting crater exhibits little evidence for interference with this early time vapor cloud. (d) In an atmosphere (0.91 bar, argon), however, the crater is significantly smaller due to pressure and drag effects. Atmospheric containment of the expanding vapor cloud and entrained impactor fragments creates a depression downrange (arrows). The combined effects of the impactor wake (Figure 7) and the downrange-moving vapor cloud scours the surface. The impactor wake and dusting created by the vapor cloud moving downrange modifies the butterfly ejecta pattern.](image-url)
were a solid block. Similar results occur for impacts into frozen carbon dioxide (dry ice).

At large scales on Venus, evidence for decapitation would include a slightly smaller depression downrange subsequently engulfed by ejecta, analogous to examples on other planets [Schultz and Gault, 1991b]. Preservation of this early time process might be much more apparent on Venus not only because of failure prior to surface contact, but also because of gravity-scaling effects on crater growth. In laboratory experiments, the fate of the projectile after impact is typically engulfed by later crater growth for loose sand targets, with final crater dimensions 40 times larger than the projectile. As impact angles decrease, energy coupled to the target decreases as \( \sin^2 \theta \) and the crater diameter reduces as about \( \sin^{1.6} \theta \) [Gault and Wedekind, 1978]. In addition, the ricochet debris reimpacts the surface at greater distances from first contact. Cratering becomes less efficient as impactor size increases, and this phenomenon is expressed by a decrease in the size of the crater relative to the projectile. A vertical impact by a 10-km-diameter impactor should be only a factor of 10 times smaller than the excavation crater diameter (precollapse of the rim by slumping or plastic flow). An oblique impact (20°) would reduce this value to about 7, comparable to the crater/projectile diameter ratio for strength-controlled craters in the laboratory. Consequently, early time processes including the downrange fate of the impactor should become more evident for large craters on Venus at less extreme oblique angles than on any other planet, except Earth [see Schultz and Gault, 1991b].

Laboratory experiments also reveal that the impact-induced vapor cloud during an oblique impact into dry ice and carbonate targets accompanies the high-speed ricochet debris downrange [Schultz, 1983a; Schultz and Gault, 1990a]. If an atmosphere is introduced (Figure 13), expansion of the vapor cloud is not only reduced (Figure 2), but the ensemble is also rapidly decelerated (Figure 13b). Figures 13c and 13d contrast the resulting effects on crater formation in carbonate and vacuum and atmospheric conditions, respectively. Under vacuum conditions the expanding vapor cloud rapidly decouples from the late stage excavation; hence the crater is unmodified. Under an atmosphere, aerodynamic drag dramatically suppresses crater growth [see Schultz, 1990a, 1991b]. More relevant for the present discussion, however, is the formation of a downrange depression created by the contained vapor cloud and the extensive scouring of the target farther downrange. In addition, the distal ejecta “wing tips” are deflected downrange, and small-scale ripples are formed uprange. Both surface effects were observed for the projectileless wake collisions (Figure 7).

Atmospheric deceleration of the downrange ricochet/vapor complex has been modelled numerically for a Venus-scale event for different size and density clouds (Figure 14). The model incorporates the simplifying assumption that the cloud does not deform by the large dynamic pressures (caveat raised by Figure 5) and represents only a first-order approximation. With this assumption, only the largest and most dense ensembles (silicate vapor cloud) can escape the impact region downrange if it does not reimpact nearby (Figure 14a). A vapor cloud that has undergone expansion or is composed of volatiles (cometary) would be permitted to travel only a few projectile radii before decelerating to near the sound speed. Hence any projectile material would be effectively trapped by the atmosphere but would be displaced downrange.

For reference, Figure 14b considers the resulting ballistic limits in terms of crater diameter calculated from equation (6) (including 25% crater enlargement) for a 28 km/s impactor with density of 3.0 g/cm^3 producing ricochet debris (or a vapor cloud) with an equivalent density and a range of dimensions shown as fractions of the original impactor dimension from 5 to 50%. These calculations serve to underscore the point that most ricochet or vapor/melt ensembles leaving the impact site at low angles (15°) should be stopped near the final crater rim. Figure 15 provides a specific example contrasting the fate of the downrange limit of low-angle debris cloud (vapor/melt/solid) from an asteroid and comet with the assumption that the cloud has expanded to twice its original volume, thereby reducing the initial density at launch by a factor of 8 from an asteroid (3.0 g/cm^3) or comet (1.0 g/cm^3). In these examples, the debris precedes the arrival of the ejecta curtain. From Figure 5a, however, high-velocity streams with little lateral dispersion (e.g., very low angle impact and ricochet) should provide exceptions to such predictions.

The rapid deceleration of the downrange vapor/melt/debris cloud converts energy partitioned into kinetic energy of high-speed target ejecta and projectile debris into internal energy of the atmosphere expressed as an intense shock and thermal turbulence. The center of this shock should be visibly offset from the crater for oblique impacts, as observed in hypervelocity oblique impacts in the laboratory under atmospheric pressure. If coupled with the vapor cloud attempting to expand in the dense atmosphere, then an oblique impact could couple more than 80% of the original impactor energy indirectly to intense atmospheric heating resembling a moving above-surface explosion [Schultz and Gault, 1990a].

As impact angles increase beyond 45°, however, the downrange velocity component decreases and the expanding impact-generated vapor/melt cloud is partly contained by the transient cavity. In laboratory experiments, this is observed as an early time reverse jet and a later time rise of a thermal "fireball"
Fig. 14. Evolution of high-speed ejecta (5 km/s) with different densities for an ejection angle of 15°. Figure 14a shows the distance traveled downrange along the ground (left) and with altitude (right) in terms of projectile diameter with different densities. Low-density ricochet debris (whether as a collection of fragments, melt, or vapor) is effectively decelerated and slides along the ground under the dense atmosphere of Venus. Large sizes represent large debris clouds resembling solid bodies. Figure 14b shows distance limit for different size ricochet debris (3.0 g/cm³) leaving at 15° from the horizontal at 10 km/s expressed in terms of crater dimensions. The ricochet debris is subjected to extremely high dynamic pressures, but failure is suppressed in the calculation in order to assess just the effects of deceleration. Relation between impactor and crater diameter uses equation (6) for reference. Figure 14b reveals that ricochet masses smaller than 10% of the original impactor mass should not escape the near-rim crater region except for the largest craters. Calculations include an exponentially decreasing atmosphere with altitude.

Consequently, the spherically expanding vapor cloud becomes more analogous with a directed jet partly contained by the ejecta plume with energy transferred to the atmosphere principally by thermal turbulence.

Since interactions between the decelerated vapor cloud and the expanding ejecta plume tied to crater growth can create turbulence, time can be as critical as dimensions. As a result, energy coupled with the atmosphere could be expressed by different styles of ejecta emplacement rather than simply the effects of an atmospheric blast. Figure 16a compares the limiting dimension of an atmospheric blast from equation (3a) with the precollapse crater dimensions and reveals that the blast limit for smaller craters has about the same dimension or smaller than the final excavation crater (precollapse). Figures 16b and 16c show the time for the blast front to decay to near sonic velocities and the time for ambient pressures to return, respectively. Figure 16b reveals that the blast becomes subsonic well before the crater has grown to its final dimensions on Venus. Consequently, the atmospheric blast limit should precede the advance of the ejecta curtain, but any surface signature for a near-vertical impact resulting in a 20-km-diameter crater (approximately) should later be consumed by crater growth. Larger craters could exhibit evidence for ejecta interactions with the atmospheric blast if not subsequently buried by ejecta. The atmospheric blast from an oblique impact, however, should interfere with ejecta emplacement downrange within a parabolic envelope widening...
resulting in secondaries. As discussed in the previous section, vertical impacts (>60ø), the rarefied atmosphere behind the shock may increase ballistic transport of ejecta perhaps principal signatures. First, the dimensions of inferred (<20 kin) grow in a shock-disturbed environment. For near-immediately after impact should be expressed by three recovery time for this fireball, its later course should be atmospheric blast effects should decrease as impactors survive much longer times to equilibrate. Because of the scale and however, since atmospheric pressures and temperatures require controlled by atmospheric circulation in addition to slope motion and the rapid deceleration of the blast front. Considerable turbulence and strong winds should persist, downrange reflecting the combination of the downrange motion and the rapid deceleration of the blast front. Considerable turbulence and strong winds should persist, however, since atmospheric pressures and temperatures require much longer times to equilibrate. Because of the scale and recovery time for this fireball, its later course should be controlled by atmospheric circulation in addition to slope effects.

In summary, energy coupled with the atmosphere immediately after impact should be expressed by three principal signatures. First, the dimensions of inferred atmospheric blast effects should decrease as impactors survive entry intact and form single craters. Second, smaller craters (<20 km) grow in a shock-disturbed environment. For near-vertical impacts (>60ø), the rarefied atmosphere behind the shock may increase ballistic transport of ejecta perhaps resulting in secondaries. As discussed in the previous section, however, trailing impactor masses shielded from the dense atmosphere within the wake of the major mass (or ensemble) also could (should) produce satellite crater fields, particularly if these masses are redirected by a strong atmospheric shock. Third, evidence should exist for a blast center consistently offset downrange from oblique impacts with late stage ejecta emplacement disrupted by the ricochet-coupled atmospheric shock or thermal turbulence. Impactor decapitation and its downrange signatures should be more evident on Venus for 50-100 km diameter craters at less extreme impact angles than on the Moon, Mercury, or Mars because of less efficient crater excavation. And fourth, even after dissipation of the shock, thermal effects and winds generated by the offset blast should be long lived. Ground-hugging density flows emerging from the fireball should exhibit slope effects, but materials at higher levels should be largely decoupled.

**Indirect Energy Transfer Signatures on Venus**

Impact-generated atmospheric blast effects related to formation of the crater Cunitz is shown in Figure 17a. The smaller crater to the north probably did not form simultaneously since there is no obvious interaction (interference) and since the inferred impact directions are different. More relevant are the bright halos around each with the absolute dimensions generally proportional with event size consistent with the craterless features shown in Figure 11b. The bright halo around Cunitz exhibits radial-bright/-dark lineations that feather distally. The halo is well developed to the east and northeast but poorly expressed elsewhere. Altimetry data (Figure 17b) reveal that the more sharply defined boundaries northwest and north of the crater (arrows) closely correspond to the edge of a plateau as shown clearly in the accompanying profiles. Areas west are lower then the crater and provide a pathway for ejecta flow. The decrease in radar brightness to the northwest is consistent with a near-surface atmospheric blast created at impact where the effects are best expressed on crater-facing slopes at higher elevation but poorly expressed in shielded, low-lying regions. This pattern contrasts with the blast halos in Figure 8 where topography has little effect except at great distances and where the overall symmetry is consistent with an air blast at altitude. The effect of the trailing wake blast and downrange winds is also indicated in Figure 17a by radar brightening of uprange ridges with radar darkening downrange. This pattern is consistent with blast winds roughening uprange-facing slopes and depositing finer fractions in the downrange lee slopes.

Scaling relations indicate that the ratio of atmospheric blast effects should gradually increase with the crater diameter if the energy partitioned to the atmosphere at impact remains constant. Figure 18 reveals, however, that this ratio systematically decreases, consistent with a gradual decrease in the energy partitioned to the atmosphere at impact remains constant. Figure 18 reveals, however, that this ratio systematically decreases, consistent with a gradual decrease in the energy partitioned to the initial blast. At small diameters (<10 km), the data seem to indicate that more than 100% of the energy is coupled to the atmosphere. This actually indicates that the central crater is smaller than expected perhaps due to objects smaller than expected surviving entry (Figures 4 and 5). Figure 18 reveals that the widespread atmospheric blast zones corresponding to craterless haloes should not be expected around craters as energy becomes indirectly coupled and expressed in other ways, e.g., turbulence. Energy transferred to the atmosphere by oblique or multiple impacts, however, should be important exceptions.

If the dark material within the interpreted blast zone is related to ablation products from the projectile, then it should be proportional to the mass of the projectile which can be calculated from equation (3a) for a given impact velocity. The amount of deposited projectile remnants falling out from the wake can be given simply as the measured area times a

![Diagram 1](image1.png)

*Fig. 15. Contrasting fate of debris or vapor cloud moving downrange at 10 km/s (15° from horizontal) for an asteroidal (upper curve) and cometary (lower curve) impactors. Assumed densities for the asteroid and comet are 0.4 g/cm³ and 0.12 g/cm³, respectively, corresponding to a factor of 2 increase in size following impact. Crater diameters are derived from equation (6) for impact velocities of 28 km/s (asteroid) and 35 km/s (comet). These two calculations indicate that cometary impacts are more likely to result in interactions with downrange ejecta since the vapor/ricochet complex decelerates more rapidly.*

![Diagram 2](image2.png)
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thickness. With these assumptions, the diameter of the dark zone should increase with the diameter of the blast limit (bright halo) raised to an exponent of 1.5. Figure 19a reveals that this is generally consistent with observations, although more data are still needed. The predicted mass of the impactor from the inferred energy release and from the radar-dark deposit provides a more informative comparison. Constraints on thickness can be made from characteristics of the radar signal [Campbell et al., this issue], but here various values will be assumed. An upper limit is inferred from the masking of preexisting topography, whereas a lower limit can be inferred from its radar detectability. If the deposit thickness is only 10 cm deep, then Figure 19b reveals that a maximum 10% of the original impactor mass survived and was deposited from the trailing wake. A deposit thickness of 50 cm would require a maximum of 2%. A considerable range in values should be expected depending on height of burst, impactor type, subsequent erosion, and impact angle. Nevertheless, these first-order estimates are well below a projectile mass, yet accommodate the observations. The remaining projectile mass presumably was completely vaporized or redistributed globally.

Although Figure 18 is consistent with a reduction in energy partitioned directly to the atmosphere as craters begin to appear, evidence for indirect coupling by high-velocity ejecta at early times also exists. Figure 20 contrasts two examples of possible interactions between early time atmospheric blast effects and ejecta emplacement. Figure 20a shows a relatively small (28 km diameter) symmetrical crater surrounded by a field of smaller impacts. The symmetry of the ejecta deposits indicates that the impact angle was relatively high (>45°). Figure 16 indicated that smaller craters on Venus may form within a shock-disturbed atmosphere that has yet to recover by the time the crater has finished forming. Under such conditions, the lower-density atmosphere should temporarily decrease the effect of aerodynamic drag, thereby allowing larger ejecta masses (including clustered masses) to survive ballistic trajectories while entraining smaller ejecta into near-rim flows. The resulting ejecta facies then would more resemble craters on Mars [see Schultz and Gault, 1979; Schultz, 1989, 1991a, c, 1992b]. Alternatively, the temporarily tenuous atmosphere would allow fragments of the initial impactor to continue to the surface at hypervelocities.

The asymmetric ejecta facies and slight uprange offset of the central peak of the crater Aurelia (Figure 20b) are consistent with a low-angle impact from the northwest [see Schultz and Gault, 1991a, b]. The elongation of the crater shape in plan transverse to the impact direction, however, indicates an impact angle between 10 and 20°, based on laboratory analogs [Gault and Wedekind, 1978]. Although the distinctive multilobed ejecta facies are best expressed perpendicular to the impact direction, the lobate pattern is disrupted downrange where it superposes fluidized flows (discussed in a subsequent section). The downrange zone of dispersed ejecta forms a relatively abrupt transition with the multilobed ejecta (arrows).
This pattern of disrupted downrange ejecta is characteristic of many craters on Venus at all scales, as further illustrated in Figure 20c, and is proposed to represent a zone of interaction between the expanding vapor cloud moving downrange and ejecta deposition. In contrast with the direct laboratory-scale comparison (Figure 13) yet consistent with extrapolations of the process (Figures 2 and 16), transfer of internal energy (cloud expansion) and kinetic energy (downrange deceleration) to the atmosphere is offset and largely decoupled from the rest of crater growth and ejecta emplacement.

Direct evidence for decoupling between early stage atmospheric response and later ejecta emplacement is shown in Figure 21. Figure 21a provides an overview of a 36-km-diameter crater that formed within a large caldera, Heng-O, revealed more clearly in the companion topographic map and profiles (Figure 21b). The role of topography on expression of the bright halo again is apparent: low-lying regions are unbrightened, while high-standing areas (above 100 m) are brightened. Abrupt borders between these contrasting areas again typically correspond to a contour matching the original preimpact elevation. Moreover, a small topographic high south of the crater appears to have formed a barrier for the blast.

Radial dark and light streaks converge not in the center of the crater but on the downrange rim where a pronounced depression (Figure 21b) extends downrange (side opposite the
zone of ejecta avoidance characterizing the uprange direction. The radar image reveals that the rim wall scarp in this region forms a straight segment (Figure 21a). Hummocky ejecta deposits beyond the rim are contained within boundary scarps closely matching the altimetry data. Highly fluid lavalike flows and a very radar-dark flow appear to originate from this downrange site.

The atmospheric blast centers on the downrange extension and clearly occurred prior to arrival of the ejecta. Such a sequence is consistent with the proposed process of indirect energy coupling with the atmosphere (Figure 1) through high-speed ejecta directed downrange. In addition, the downrange depression closely resembles morphologies associated with oblique impact craters on the Moon, Mars, and Mercury and is
interpreted as a consequence of the debris ricochet reimpacting at hypervelocities [Schultz and Gault, 1991a, b]. The principal difference between such craters on Venus and on other planets is the subsequent engulfment by ejecta and the emergent lava-like flows.

In summary, energy directly transferred to the atmosphere at impact represents a significantly smaller fraction (<1%) of the initial impactor energy unless decoupled from the crater cavity through downrange ricochet debris and accompanying vapor/melt. On other planets, the downrange velocity of the vapor cloud from oblique impacts (50-80% the impactor velocity, i.e., 8-15 km/s) exceeds its expansion velocity (3-5 km/s). Consequently, signatures of surface interactions are rare

unless the impact occurs on the rim or floor of a much larger crater [Schultz and Gault, 1991a]. On Venus, the extraordinary expression and frequency of this process most likely result from the following phenomena: decrease in cratering efficiency (therby exposing this process), projectile failure/redirection as it "feels" the surface prior to contact through the compressed air cap, and containment/deceleration of the ricochet/vapor/melt cloud by the dense atmosphere. Expressions of this process include an inferred blast source offset downrange, downrange rim depressions subsequently engulfed by later arriving ejecta, and interference with downrange ejecta emplacement in a parabolic envelope open downrange. Conversely, decoupling of the blast center from the point of first contact exposes late stage ejecta to the full aerodynamic interactions with the atmosphere. Since most impacts occur near 45°, this scenario should be typical, yet it is distinct from the frequent analogies with stationary, above-surface explosions. Finally, containment and deceleration of the ricochet/vapor/melt cloud means that the impactor may not be completely lost on Venus. The highly fluid flows originating on the downrange rim are consistent with retention of the impactor (Figures 18 and 19).

3. SEQUENCE AND STYLES OF EJECTA EMPLACEMENT

The preceding analysis outlined and documented possible conditions immediately following impact. This section examines expected and observed processes occurring during later stages of crater excavation and ejecta emplacement.

Atmospheric effects

Emplacement of ejecta under atmospheric conditions is controlled not only by the response of the fragmented ejecta to the dense atmosphere but also by the atmospheric response to both the mechanically driven crater excavation process and thermally driven processes related to the expanding/moving vapor cloud at early times. Laboratory experiments allow recognizing these contrasting responses but cannot directly simulate all processes at all scales simultaneously.

The response of ejecta to an atmosphere occurs on two scales: direct aerodynamic drag acting on individual ejecta...
fragments and drag acting on an ensemble of fragments, whether comprising the ejecta curtain or a ray. The contrast in response was illustrated by the aerodynamic deceleration of a hypervelocity cluster (Figure 5). It is also illustrated by early time growth of the ejecta curtain where even the finest particles leave the cavity on ballistic trajectories and define a conical ejecta curtain similar to ejection under vacuum conditions. As described in more detail elsewhere [Schultz and Gault, 1979, 1982], development of the classic conical ejecta plume at early time reveals the reduced aerodynamic pressure within an ejecta stream, i.e., \[ \frac{1}{2} \rho_0 (\Delta v)^2 \text{ where } \Delta v \text{ is the difference in velocity between individual ejecta in the curtain and the ambient atmosphere.} \]

During initial crater growth, the ejecta stream parallels the curtain and \( \Delta v \) develops by disruption of the boundary layer between the curtain and the surrounding atmosphere. At late stages of crater growth, ballistic ejecta within the curtain no longer parallel the curtain but progressively become perpendicular both with distance above the surface and with time. Consequently, \( \Delta v \) and hence aerodynamic drag acting on individual particles increase substantially. In the absence of other processes (turbulence, atmospheric blast, etc.), debris surviving initial ballistic ejection can now be subjected directly to large aerodynamic stresses.

Aerodynamic drag on given size ejecta increases with increasing crater size \( (R) \) since ejection velocities increase as \( (gR)^{1/2} \) [see Post, 1974; Schultz and Gault, 1979; Housen et al., 1983]. The effect of scale can be appreciated by simply extrapolating ejection velocities at various stages of crater growth from computational codes [Orphal et al., 1980] to larger size craters on Venus (Figure 22a). For convenience, stage of crater growth is given as the size of the cavity scaled to the final excavation crater. Since ejection velocities progressively decrease with stage of crater growth, ejecta will be subjected to different aerodynamic stresses. Figure 22b reveals that even ejecta avoiding atmospheric interactions during launch (whether due to ballistic shadowing or within a region of reduced density due to a strong shock) nevertheless would be subjected to extreme stresses during reentry. Consequently, shocked material excavated from a major crater on Venus should be further pulverized by the stresses associated with aerodynamic drag unless entrained and protected within bulk lower velocity ejecta at the final stages of growth.

Laboratory experiments reveal that the kinematic response of the atmosphere to the outward moving ejecta curtain largely controls the style of ejecta emplacement [Schultz, 1992b]. Since the ejecta curtain is attached at the base to the growing crater cavity, it creates a classic pattern of redirected airflow in front of an inclined plate. The boundary layer between the atmosphere and the upward moving ejecta within the curtain (prior to completion of crater formation) depends on the Reynolds number, which varies along the curtain since the free-stream airflow velocity varies. At the base of the curtain, lower Reynolds numbers occur around a stagnation zone, visible in shadowgraphs [Schultz and Gault, 1982]. As the Reynolds number increases, the boundary layer thickness decreases farther up the curtain until turbulence interferes with individual ejecta, thereby initiating shear drag and reverse flow visible as a small toroidal bump on the curtain [see Schultz and Gault, 1982; Schultz, 1992b]. The vortex moves up the curtain and expands in laboratory experiments at late times. In addition, the outward moving curtain creates a partial vacuum behind it. As the upper portions of the curtain thin, the atmosphere is observed to rush into the cavity, and this response creates a vortex entraining sufficiently small ejecta behind the advancing curtain. Essentially, the ejecta curtain creates a violent wind that interferes with simple ballistic deposition and drives the ejecta cloud outward.

The contrasting evolution of the ejecta curtain under different atmospheric densities illustrates the effect of ejecta entrainment (Figure 23). Entrainment is controlled by aerodynamic drag and hence atmospheric density for given values of target, impactor, and pressure. Figure 23a reveals the systematic outward advance of the inclined ejecta curtain under vacuum conditions as described by Gault et al. [1968] and Orphal et al. [1973]. Under a 1-bar atmosphere (low density), this outward moving inclined ejecta curtain is also preserved even though ejecta emplacement and cratering efficiency are affected [Schultz, 1992b]. Under a 1-bar atmosphere of air, the inclined ejecta curtain gradually steepens with time, eventually forming a bulge and outward ejecta flow at the base (Figure 23b). This response reflects the combined effects of ejecta entrainment and the basal vortex created by the pressure differential in front of and behind the curtain. A fundamental difference between the laboratory experiment and Venus, however, will be the size of turbulence relative to the size of the crater. On Venus, the very high Reynolds numbers and high atmospheric pressure will result in much smaller turbulent eddies relative to the crater. Consequently, the basal ejecta run-out should hug the ground more closely.

The laboratory experiments are particularly relevant for ejecta emplacement around larger craters (> 5 km) on Mars, where the low atmospheric density is offset by the high ejection velocities, thereby creating large aerodynamic drag on ejecta below a critical size [Schultz and Gault, 1979]. The typical range of in situ and postimpact ejecta sizes result both in winds created by the ejecta curtain and in entrainment of smaller size fractions. Under conditions of partial ejecta entrainment, the ejecta run-out distance \( x \) from the rim of a crater of radius \( R \) can be written simply as [Schultz, 1992b]

\[ (x/R) \sim (R/g)^{1/2} \]
Fig. 21a. Evidence for indirect energy coupling with the atmosphere due to high-speed vaporization at early times: a 36-km-diameter crater produced by an oblique impact from the northwest (4.5°N, 356°). Radial radar-bright lineations (white lines) converge on the downrange rim rather than crater center. The downrange crater wall region is narrower and forms a straight segment downrange suggestive of a lower rim height. Lobate flows appear to emerge from an elongate depression (D) on the southeast rim delineated by a narrow scarp (medium-size, black arrows). Radar-bright stippled ejecta extend downrange and grade into a sharply bordered radar-dark flow.
Consequently, ejecta run-out distance should (and does) increase with crater size on Mars and under certain conditions in the laboratory [Schultz, 1992b]. On Venus, however, the dense atmosphere results in nearly complete ejecta entrainment resulting in ejecta run-out distances around craters on Venus that decrease with increasing size:

\[
\frac{x}{R} \sim R^{-1/2} 
\]

(11a)

where ejecta flow density is a constant fraction of ambient atmospheric density, and

\[
\frac{x}{R} \sim k 
\]

(11b)

where ejecta flow density approaches atmospheric density. Conditions leading to equation (11b) result in turbulent flows that entrain finer fractions and continue to run out after coarse ejecta are deposited near the rim.

The style of ejecta emplacement depends not just on the degree of entrainment but also on turbulence and winds created in response to the outward moving ejecta curtain. In the laboratory, toroidal winds trailing the ejecta curtain mobilize coarser ejecta fractions until the wind-driving force (the advancing curtain) ceases, thereby depositing the load and forming terminal ramparts. As ejecta sizes decrease (given atmospheric pressure), the toroidal afterwinds break into turbulent motion with long individual run-out flows. Under such conditions, trailing vertical winds are strong enough to literally erode and scour the inner deposits. Moreover, flow separation (where the flow in the boundary layer becomes reversed) occurs behind the leading ejecta front. Ejecta entrained in this flow runs over and beyond the terminus of the inner deposits. Ejecta sizes entrained in this extended flow should be characteristic of "wind sensitive" particulates, i.e., grains easily suspended and transported by ambient winds, in contrast with coarser ejecta comprising the ramparts or inner ejecta deposits. The same distinction in style was proposed for the origin of Martian ejecta flows, except that enhanced run-out
Fig. 22a. Outward velocity of the ejecta plume (curtain) during crater growth for different diameter craters scaled according to \( R^{1/2} \) from the numerical code results of Orphal et al. [1980]. Stage of growth is shown in terms of both transient radius scaled to final excavation radius (bottom) and the percentage of mass ejected (top). Extrapolations to later stages assume ballistic velocities decrease with a -2.7 power law. Most of ejecta curtain advance occurs at subsonic velocities. Crater sizes represent apparent excavation diameters (referenced to preimpact surface). Observed rim-to-rim diameters will be about a factor 1.56 larger (25% for correction to rim-rim diameter, 25% for enlargement by slumping).

Could occur if volatiles are also released [Schultz, 1986, 1991a, 1992b].

For Venus, the dense atmosphere results in a high Reynolds number with enhanced turbulence. The outward momentum of the ballistic ejecta curtain is sustained by both strong recovery winds trailing the advancing curtain and slopes created by the raised rim. Consequently, lobate flows should dominate the emplacement style. Flow separation and continued run-out of entrained smaller debris should occur beyond the inner facies. Rampartlike borders could develop where/when turbulence decreases sufficiently to allow eddy-driven suspension of coarse debris.

These descriptions are based on the systematic sequence of ballistic ejection and atmospheric response as observed in the laboratory. Two processes can further modify the emplacement style. First, oblique impacts in the laboratory create strong downrange draughting, i.e., afterwinds created by the trailing wake and the partial vacuum behind the ricochet complex (Figure 13). Second, vaporized material was shown to be contained and decelerated under the dense atmosphere on Venus (Figures 14 and 15). Consequently, the internal energy (thermal turbulence) contained in this cloud should significantly disrupt ejecta emplacement downrange.

In summary, the following generalized styles and sequence of emplacement should be expected on Venus. First, the vapor cloud created at early times by oblique impacts (< 50°) should form a separate and distinct style of ejecta emplacement downrange prior to arrival of the late stage atmosphere-entrained ejecta. Impact direction will control the flow direction initially with local slopes controlling its subsequent course. Because lower atmospheric pressures in the downrange fireball persist over longer times (Figure 16c), density flows of
molten droplets resembling nubes ardentes should develop. The downrange vapor/melt/debris cloud is proposed to contain most of the impactor (prevented from escaping); consequently, impactor type could play a role in the subsequent evolution of such density flows. The volume of material contained in this type of run-out deposit should remain below a few projectile masses, regardless of crater size, but volume should increase with decreasing impact angle. Second, heating of the atmosphere by the strong atmospheric shock evolves into a rising fireball that expands with altitude. The rolling vortical motion entrains and carries smaller size ejecta not only to high altitudes but also downrange. Third, evidence should exist for ballistic ejection but nonballistic emplacement of the late stage ejecta as part of a turbulent basal flow. The maximum ejecta run-out distance should decrease with increasing crater size. Fourth, crater interiors should not exhibit massive fallback or fallout debris since drag-decelerated ejecta become entrained in outward moving turbulent flows on the surface or are entrained in the fireball aloft. Fifth, the inner ejecta deposits will be scoured by intense turbulence and winds due to the pressure differential in front of and behind the ejecta curtain. Sixth, flow separation at the ejecta flow head after collapse of the curtain results in extended run-out of "finer" debris flows beyond the bulk ejecta. Seventh, evidence should exist for redirected ejecta flow and atmospheric winds in response to draughting created by downrange high-speed ejecta at early times. The last four conclusions are based on analyses prior to Magellan arriving at Venus but were applied to expected atmospheric effects for impacts on Mars and Earth [Schultz and Gault, 1979, 1982; Schultz, 1981]. The first conclusion is also based on earlier analyses [Schultz, 1988a, 1991a, b; Schultz and Gault, 1990a], and finds direct support in the detailed cratering record revealed by Magellan [Schultz, 1991c, d].

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parabolic pattern, wind streaks, and lobate flows are all signatures of early time processes and are the focus for this section. Later emplacement of ejecta is considered in the following section.

Phillips et al. [1991] and Arvidson et al. [1991] recognized the parabolic-shaped radar-dark zone enveloping Carson about 130 km to the east and noted that this appeared to be a common feature for well-preserved craters within about ±30° of the equator (Figure 24a). They suggested that the parabola represents fine-grained ejecta that interacted with high-speed (100 m/s) westward winds occurring 60-70 km aloft. Figure 24a reveals that Carson is offset well north of the axis of symmetry of the parabola; that is, the parabola is offset downrange from the direction of impact. Because the radar-darkened pattern crosses all ejecta facies (Figure 24b), it represents fallout and redistribution of fine debris after crater formation and after ejecta emplacement as suggested in the earlier reports. Radar-bright streaks behind small relief domes indicate wind directions deflected outside the parabola as far as 175 km east of Carson (Figure 24a). Within the parabola, however, streaks converge on a point downrange, very similar to the streaks shown in Figure 21. Figure 24c reveals that wind direction is affected by topography [Arvidson et al., 1991] but also there is a pattern controlled by distance and direction from Carson. Thus the formation of Carson generated an atmospheric response longer lived than crater formation and resulted in both radar-dark and radar-bright wind streaks associated with topographic relief.
Fig. 25. The effect of impact direction and latitude on expression and asymmetry of the radar-dark parabolic patterns. Figure 25a shows a small crater Rose (15 km in diameter at 35°S, 249°) formed by an impact from the southwest. The pronounced offset in the point of symmetry in parabola to the northeast seems to center on a point downrange as noted for Carson (Figure 24). This crater exhibits unusually radar-bright flows downrange, and the parabola exhibits low emissivity suggestive of compositional contrasts. Figure 25b shows the 50-km-diameter Cunitz (14.5°N, 351°) formed by an impact from the east-southeast, based on ejecta asymmetry (see Figure 17). Although well-defined radar-dark/bright lineations are evident, the parabola pattern has not developed. Figure 25c further illustrates the absence of a radar-dark parabola for a low-latitude crater formed by an impact from the east (26°N, 14°E; C1-30N009). Arrows indicate direction of diffuse radar-bright deposits at the base of low-relief hills. These deposits are interpreted as coarse materials dislodged by a strong downrange atmospheric blast and winds. Figures 25a, 25b, and 25c are consistent with radar-dark parabolas developing from standoff between upper level easterlies and a debris-laden fireball directed downrange. Figure 25d illustrates a 40-km-diameter high-latitude (70°N, 110°) crater with a well-defined radar-dark parabola. Such a pattern at high latitudes seems to conflict with the inferred role of upper level winds (Figures 25a-25c). More likely, it represents the effect of the atmosphere limiting expansion of a dust-laden fireball. Hence the role of upper level winds is believed to principally accentuate or destroy the parabola pattern depending on impact direction but they are not necessary for formation.

Not all craters in the equatorial zone exhibit well-developed parabolic patterns. In some cases, this appears to be a function of relative age. In others, however, it is a function of impact direction (Figure 25). Even very small craters formed by impacts (Figure 25a) from the west (into the westward winds aloft) develop a well-defined parabolic pattern. Impacts from the east, however, generally do not (Figures 25b and 25c) unless crater diameter approaches the altitude of the westward wind flow. The 50-km-diameter crater Cunitz (Figures 17 and 25b) formed by an impact from the east at a low latitude (15°) exhibits well-preserved blast striations but is not enveloped by a radar-dark parabola or emissivity contrast. Similarly, the crater in Figure 25c is not associated with a pronounced parabola or emissivity signature. Yet much smaller craters (<30 km) formed by impacts from the west can exhibit pronounced parabolas and asymmetry as illustrated by the 15-km-diameter crater Rose (Figure 25a). Small craters typically exhibit a relatively narrow parabolic outline, whereas large craters are embedded in radar-dark materials that fill in the outline. Impacts from the southwest or northwest exhibit different degrees of asymmetry with the northern or southern wing of the parabola, respectively, exhibiting enhanced emissivity contrast depending on trajectory azimuth. Large offset parabolas around small craters are difficult to understand if the
Fig. 26a. Wind streaks and radar-dark deposits associated with the 66-km-diameter crater Seymour formed by an impact from the south at low latitudes (18°N, 326.5°), providing an overview including the crater Aurelia and its distinctive parabola to the east (Figure 26b). A radar-dark boundary envelopes a radar-bright zone over 700 km downrange, whereas a complex swirly pattern superposes the Aurelia parabola.

Fig. 26b. Closer view of wind streaks and fluidized flows associated with the crater Seymour shown in Figure 26a. Muted radar-bright lenticular patterns associated with low-relief mounds appear to be associated with the downrange emplacement of long, fluidized, run-out flows. Radar-bright zones covered by these fluidized deposits remain visible and are directed away from the downrange area. One of the domes exhibits a radar-bright area directed both toward and away from this region. It is suggested that the strong atmospheric blast created by the downrange ricochet/vapor cloud dislodges coarse materials on exposed relief which are then entrained in winds first directed away from, then back toward the downrange "source" area analogous to the atmospheric response to above-surface bursts. Draughting created behind this rising and moving fireball is suggested to be responsible for reworking the radar-dark deposits at much later times, including deposits associated with Aurelia. Redirected upper level winds combined with rising downrange fireball also may have produced the spiral-like pattern centered on the downrange blast zone (upper left).

The parabolas simply reflect the collision between the ejecta curtain and the westward winds aloft [Arvidson et al., 1991; Campbell et al., this issue]. Nevertheless, direct interference between the curtain and winds aloft should occur for high-angle impacts producing a crater with dimensions approaching the altitude of these winds. Figure 25d illustrates a crater with a parabola at very high latitudes. Consequently, either an additional upper level wind is indicated or the parabola results from another (or even additional) process, such as winds induced by the moving, density-laden fireball.

Figure 26 allows comparison with the larger crater Seymour (66 km) produced by an oblique trajectory opposite to Carson, i.e., from south to north but also at low latitudes. The overview in Figure 26a shows a radar-dark boundary over 700 km to the north, downrange from the impact, rather than to the east. Uprange, swirly radar-dark deposits converge on the crater and appear to interrupt deposits from Aurelia. A closer view (Figure 26b) reveals that the radar-dark boundary of Aurelia is serrated with striations directed back to the larger crater to the west. Radar-bright wind streaks again occur to one side of low-relief volcanic domes, and generally are directed radially from a focus downrange. East of the crater, bright streaks generally are directed away, whereas to the west, they can occur in either direction. Two small domes to the northeast exhibit radar-bright deposits covered by subsequent run-out flows and directed away from the downrange axis. To the northwest, the streak pattern parallels the direction of the long run-out flows but then diverts downrange. Linear radar-dark wind streaks appear to encroach and mantle the downrange ejecta deposits from the east.

Fig. 26c. Teardrop-shaped zones in lee of low relief hills downrange from the crater Seymour. Strong winds created by the downrange-moving fireball created horseshoe vortices that wrapped around obstacles and scoured the surface of finer materials analogous to patterns produced in the laboratory and observed on Mars [Greeley and Iverson, 1985]. Winds appear to separate from the slope-controlled run-out flows farther downrange.
Fig. 27a. Schematic for impact-generated winds based on inferences from wind streaks around the 38-km-diameter crater Carson (Figure 24). Near-surface winds at Carson are initially directed downrange by the expanding vapor cloud and wake winds (solid arrows). Recovery winds behind the blast (dashed arrows) are drawn back to the downrange rim region where most of the impact energy was coupled to the atmosphere following impact due to rapid deceleration and containment of the vapor cloud. Strong and sustained winds appear to deflect uprange around the eastern edge of the blast limit represented by the radar-dark parabola. As the fireball moves downrange and increases in height, it undergoes runaway expansion in the lower atmospheric densities at upper levels (right) analogous to the computed evolution of strong explosions on the Earth [Jones and Kodis, 1982]. Upper level winds are deflected around this higher-density region and perhaps were directed downward by collapse of the fireball or "cooler" temperatures (relative to the atmosphere around the impact). At very late times, turbulence created by the impact is carried westward by winds aloft. At Carson, long-lasting turbulence apparently reached the surface in order to account for redistribution of radar-dark material to the east and the erosional scouring to the west (left).

Fig. 27b. Near-surface winds associated with the impact producing the 66-km-diameter crater Seymour in Figure 26 were drawn downrange (northward) behind the fireball and perhaps ricocheted debris. Topography redirected the base of the disturbance, as indicated by scouring in the lee of small volcanoes. Entrained ejecta within the fireball created a density flow redirected by a linear E-W depression. Fallout from the impactor during entry is also drawn downrange but some material reaches the ground to form dispersed, mottled radar-dark deposits uprange. Alternatively, these mottled deposits are remnants of parabola deposits from Aurelia that were drawn downrange by this more recent impact. Aloft (right), the upper level easterlies are drawn northward behind the expanding fireball and debris as they move downrange. Hypersonic reentry debris forms Tunguska-like air blasts downrange and a radar-bright ring nearly 300 km in diameter centered 450 km downrange. At this range, reentry velocities would approach 3 km/s. Some of this debris reaches the surface to form small craters 350 km downrange. Serrated border of the parabola associated with Aurelia, mantling of ejecta flows, and E-W lineations suggest that the disturbance also resulted in strong westward surface winds perhaps driven by the relict fireball as it was carried by the reestablished circulation aloft.
The teardrop-shaped streaks in Figure 26, however, are not radial but exhibit trends controlled by both impact direction and local slopes. These wind streaks are suggested to be associated with the longer lived fireball moving downrange. Horsehoe-shaped vortices are created by deflection of flow around obstacles within the turbulent fireball, and winds in the vortices scour away loose materials in the lee of topographic highs, analogous to wind streaks on Mars [see Greeley and Iverson, 1985]. The teardrop-shaped streaks in Figure 26 occur within a curvilinear zone trending northward to a series of radar-bright haloes, one of which contains small craters. The downrange location of these radar-bright haloes suggests that they may represent air blast effects created by high-speed reentry ejecta (or ricochet). Because the downrange fireball is largely decoupled from the surface, it continues downrange and creates strong draughting. Trailing surface winds beneath the fireball, however, should exhibit orographic effects (i.e., deflection by topography). The combined motion of the downrange fireball, inferred ricochet blast, and upper level recovery winds appear to produce a spiral-shaped pattern centered downrange.

Topographic data for the region around the crater Seymour in Figure 26 reveal that WNE-SEE linear depressions cross downrange. Very late stage density flows channelized within these transecting troughs probably produced the anomalous ESE trending streaks. Uprange the winds may have created the complex radar-dark patterns and eroded the Aurelia parabola. Consequently, the radar-bright wind streaks could have a variety of origins depending on topography, impact direction, and time (evolution of the atmospheric response from the initial blast).

The radar-dark parabolas are suggested to reflect a still longer, upper level response to the downrange moving blast and fireball. As the fireball moves downrange and expands into the less dense upper atmosphere, it accelerates in runaway growth with a leading boundary of higher density than the surroundings, analogous to high yield explosions on Earth modeled by Jones and Kodis [1982]. The atmosphere deflects around this expanding inclined barrier at near supersonic speeds and creates strong wind shear. The greater density of the front and the material entrained within the fireball produces a well-defined parabolic interface with the surrounding atmosphere. If the impact direction is from the west, this interface is accentuated by the strong winds aloft. Turbulent cells within a donut-shaped ring vortex should entrain and suspend ejecta and melt particles to high altitudes. The evolution of such a thermal vortex within the ejecta curtain in impact experiments has been previously documented [Schultz and Gault, 1982]. Fallout from the expanding vortex around smaller events may occur only along the parabolic interface.

### TABLE 2. Effect of Impact Direction on Parabola Patterns

<table>
<thead>
<tr>
<th>Impact direction (clockwise from south)</th>
<th>Craters &lt;50 km</th>
<th>Craters 50-250 km</th>
<th>Complex Terrains</th>
<th>Multiple</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-90</td>
<td>11</td>
<td>2</td>
<td>1</td>
<td>-</td>
<td>14</td>
</tr>
<tr>
<td>90-180</td>
<td>8</td>
<td>2</td>
<td>-</td>
<td>-</td>
<td>10</td>
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<tr>
<td>180-270</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>6</td>
</tr>
<tr>
<td>270-360</td>
<td>2a</td>
<td>1</td>
<td>2</td>
<td>1</td>
<td>6</td>
</tr>
<tr>
<td>Total</td>
<td>21</td>
<td>6</td>
<td>5</td>
<td>3</td>
<td>36</td>
</tr>
</tbody>
</table>

Data are from Table 1 of Campbell et al. [this issue] excluding the following craters for which impact directions cannot be clearly determined as yet: Cohn, Monika, Audrey, Commens, La Quinziao, Lyon, Akiko, Gaspell, Meri-Pah, Holiday, and Austen.

a Both craters are at high latitudes and are large.
The effect of impact direction and crater size is tested in Table 2 and Figure 27c. Table 2 reveals that 67% of the craters associated with parabolas were produced by bodies impacting to the east, into the winds aloft. On the basis of experiments, impacts into complex terrains (fractured, hilly) can enhance coupling with the atmosphere. Moreover, the ejecta plume from large craters (> 50 km in diameter) should directly interfere with winds aloft, thereby overriding the effect of an early time atmospheric blast. Without these two subsets, 90% of the craters with parabolas given by Campbell et al. [this issue] now result from impacts directed to the east. Figure 27c shows the effect of impact direction and crater size for craters formed on plains units and reveals that the parabola apex distance appears to be a large-scale manifestation of air blast effects shown in Figure 18.

The nature of the material causing the low radar backscatter requires more detailed studies as by Campbell et al. [this issue]. Based on geologic studies of terrestrial impacts and impact materials, large quantities of recondensed vapor and melt products (i.e., glassy spheres, tektitelike objects, and suevitic glasses) most likely comprise the fallout material. If the object forming the 38-km-diameter crater Carson was about 5 km in diameter, then it represents a mass of 1.6 x 10^{17} g (assumed density of 2.5 g/cm^{3} and impact velocity of 28 km/s from equation (6)). A projectile mass of fallout material spread over the area represented by the enveloping parabola (10^{6} km^{2}) would produce a deposit thickness of 14 cm (bulk deposit density of 1.2 g/cm^{3}) and would represent about 7% of the excavated crater mass. The total mass in this deposit is only 2 orders of magnitude greater than the estimated mass in the 700,000-year-old North American strew field [Glass, 1982] for which there is no recognized crater. Table 3 provides a comparison of the deposit mass around Carson with the estimated total mass associated with tektites [Glass, 1982]. Since bright-haloed air blast zones (Figure 8) do not produce parabolic patterns, the nature of the radar-dark material should include considerable target material, analogous with the target-dominated tektite-strewn fields. Superposition of a wide range of geologic units and topography by the radar-dark pattern is consistent with this scenario, rather than widespread smoothing to meter scales.

In summary, radar-bright streaks and radar-dark parabolic pattern are contrasting expressions of the atmospheric response to the early time vapor cloud moving downrange. Radar-bright streaks radial to the downrange rim are proposed to indicate early time shock dislodgement and transport of large debris from the most intense overpressures and winds from the initial blast. Radar-bright teardrop-shaped patterns associated with mounds and domes, however, are suggested to represent scour zones created by horseshoe-shaped vortices induced by obstacles within the turbulent fireball at later times. The radar-dark parabola also reflects a response to the early time blast but represents much later fallout from the later stage.

### TABLE 3. Comparison Between Terrestrial Tektite Strewn Field Masses and Paraboloid Deposit Mass Associated With Canon

<table>
<thead>
<tr>
<th>Region</th>
<th>Source Crater</th>
<th>Diameter, km</th>
<th>Impactor Mass, x10^{12} g</th>
<th>Area, x10^{6} km^{2}</th>
<th>Deposit Mass, x10^{14} g</th>
<th>Deposit/Impactor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Australasiana</td>
<td>Zhamanshin</td>
<td>10</td>
<td>4</td>
<td>50</td>
<td>1</td>
<td>0.25</td>
</tr>
<tr>
<td>Ivory Coastb</td>
<td>Bonamtwi</td>
<td>10.5</td>
<td>5</td>
<td>4</td>
<td>0.2</td>
<td>0.04</td>
</tr>
<tr>
<td>N.Americanc</td>
<td></td>
<td>7</td>
<td>7</td>
<td>57</td>
<td>10</td>
<td>0.62</td>
</tr>
<tr>
<td>Paraboloid</td>
<td>Carson</td>
<td>48</td>
<td>1600</td>
<td>1000</td>
<td>1000</td>
<td></td>
</tr>
</tbody>
</table>

a From Glass [1982].
b A deposit mass of 10^{12} g spread uniformly over the paraboloid associated with Carson would produce an 8-cm-thick layer with a bulk density of 1.2 g/cm^{3}.

d In summary, radar-bright streaks and radar-dark parabolic pattern are contrasting expressions of the atmospheric response to the early time vapor cloud moving downrange. Radar-bright streaks radial to the downrange rim are proposed to indicate early time shock dislodgement and transport of large debris from the most intense overpressures and winds from the initial blast. Radar-bright teardrop-shaped patterns associated with mounds and domes, however, are suggested to represent scour zones created by horseshoe-shaped vortices induced by obstacles within the turbulent fireball at later times. The radar-dark parabola also reflects a response to the early time blast but represents much later fallout from the later stage.
Figure 28. Closer views of the early time emplacement of long run-out flows (Figures 28a and 28b) and later ejecta (Figures 28c and 28d) associated with the 38-km-diameter crater Carson (see Figure 24). Lobate flows appear to originate on the downrange rim of Carson but are then clearly controlled by the local slopes (Figure 24c). The sharply defined flow boundary is muted but otherwise unaffected or obstructed by emplacement of ejecta (small arrows, Figures 28a and 28b). The flows were emplaced as a liquid since low-relief mounds formed kipukas (islands) in Figure 28b. White arrow in Figure 28a identifies a small crater pair that might be due to secondaries. Sequence of formation (smaller downrange on top of larger uprange crater), however, is more suggestive of late arriving fragments associated with partial disruption of the major impacting body responsible for Carson (see Figure 4). Figures 28c and 28d illustrate later emplacement of ejecta from crater excavation. The uprange zone of avoidance (Figure 28c) indicates ballistic ejection with convergent sector locating the limit of the transient crater. The curving distal ejecta deposits, however, indicate influence of strong winds created by the downrange advance of both the vapor cloud and ejecta curtain. Figure 28d shows the effect of a 300-m-high hill to the east (see Figure 24c) on ejecta emplacement. Small white arrows indicate standoff and redirection of radar-bright ejecta flow at a level 100-200 m above the preimpact surface. Large white arrow, however, identifies a radar-dark flow with a greater run-out distance, although the maximum relief remained as a barrier. Such a pattern of emplacement is consistent with flow separation created at the head of a basal debris flow of ejecta. Turbidity within this separated flow entrains finer fractions and creates further run-out, analogous to ejecta flows observed in laboratory experiments and in other larger-scale turbidity flows. Medium-sized arrow in Figure 28d identifies satellite craters possibly indicating secondaries or smaller impactor fragments shielded in the wake of the major mass during entry.
fireball, perhaps analogous to dispersed impact materials on Earth. Consequently, the parabolas around impact craters are large-scale manifestations of the air blast haloes (Figure 8) except that the air blast is generated after impact and is laden with impact debris.

Ejecta emplacement. Phillips et al. [1991] described the enigmatic lavalike flows extending from the crater Carson (Figure 24) as further illustrated in Figures 20, 21, and 26. Such flows appear to emerge from the downrange rim region, prior to the emplacement of the radar-bright hummocky ejecta deposits. Such a sequence is consistent with the hypothesis that they evolved from a density flow collapsing within the atmosphere-contained fireball downrange.

The impact vapor cloud from an oblique impact moves rapidly downrange well ahead of the bulk ejecta (Figure 15) while rapidly evolving into a high-temperature, low-density fireball (Figure 16b). The long, radar-bright lavalike flows shown in Figure 21 were suggested to be signatures of this process, and Figure 28 provides closer views of supporting observational evidence for this timing and style of emplacement. Figure 28a reveals that the lobe to the west extends beneath the speckled, hummocky ejecta. Boundaries of this lobe simply become ill defined where the deposit becomes thicker, but neither the ejecta nor the flows show evidence for interaction. A similar sequence occurs to the east (Figure 28b) where unburied regions (kipukas) remain identifiable through the downrange hummocky ejecta. Both lobes originate from a region directly downrange as inferred from the distinctive zone of ejecta avoidance (Figure 28c) diagnostic of the uprange direction in oblique impacts.

Although the inferred source region of the flows is controlled by impact direction, subsequent flow is clearly controlled by local slopes. This can be demonstrated in Figure 24c, which shows the Magellan altimetry data for the region around Carson. The reliability of the altimetry data in less complicated terrains can be demonstrated by how closely the flows follow the local slopes, even to the scale of subtle redirection. Figure 28c also reveals that the northeast extension of the eastern lobe (Figure 28b) appears to originate on a downrange topographic high. The apparent "source" region now appears not just to be downrange but also upslope. In the context of the working hypothesis, it is suggested that the expanding vapor cloud near the surface decelerated within 10 projectile diameters downrange where it collided with the crater-facing hill, collapsed from the confining pressure of the Venus atmosphere, and split into two high-temperature flows following the local slopes.

Because of the unique signature of the long run-out flows and apparent association with the impactor (direction and angle), the following section will consider further tests for their proposed origin. Here attention now focuses on late stage ejecta emplacement processes, i.e., following deceleration, collapse, and slope-controlled emplacement of the contained impact vapor cloud. Four craters will be used for illustration. The crater Carson and the example in Figure 26 are again used to compare emplacement processes around two different size oblique impacts (38 km and 66 km in diameter, respectively). These are then contrasted with 70-km- and 170-km-diameter craters formed by higher-angle trajectories.

The radar-bright ejecta deposits around Carson provide evidence for late stage ballistic ejection but nonballistic

![Fig. 29. Ejecta emplacement sequence and style near the rim (Figure 29a) and at greater distances downrange (Figure 29b) for the 66-km-diameter crater Seymour examined in Figure 26. Ejecta (white arrows) adjacent to the uprange rim are blocked by a low-relief mound. Similar deflection around small obstacles occurs downrange (black arrow). Blockage indicates collapse of the ejecta curtain into a ground-hugging flow similar to evolution observed in the laboratory (Figure 23b). Radial ejecta lobes extend east and west, perpendicular to impact direction. Downrange ejecta flows form a complex networked pattern with anastomosing channels indicative of turbulent and multistaged emplacement. This downrange zone is proposed to indicate interactions between ballistic ejecta and remnants of the downrange turbulent fireball. Redirected flows to the west also suggest sustained turbulent run-out. Figure 29b shows the downrange emergence and run-out of laminar emplacement style. Altimetry data reveal that the flows cascade over the edge of a plateau into a NW-SE valley. The flow thickens with distance from the rim as indicated by exposed preexisting features (domes, ridges) on the plateau (arrow A) and burial at the termini. Radar-dark materials superpose this sequence due, at least in part, to deposits from a density flow originating at the fireball downrange equilibrated and was channelized at very late time along the NW-SE valley floor. Heat released from the vapor cloud as melt phases condensed may have produced additional overriding turbidity flows down the valley. Radar-dark streaks are suggested to be reworked deposits from the preexisting crater Aurelia (to the east) drawn westward by strong surface winds associated with this impact (see Figure 26).]
emplacement. Evidence for ballistic ejection includes the well-defined uprange boundary forming the avoidance zone of ejecta analogous to craters under vacuum conditions (Figure 28c). If ejecta were ejected by an explosive process, then the zone of avoidance would not be preserved. It should be noted that an uprange zone of avoidance develops at early times in laboratory experiments (particulate targets under vacuum) even at modest impact angles (45°) but is lost at late times beneath near-rim ejecta. Asymmetry in ejecta deposition is nevertheless expressed in a more rapid decay in ejecta thickness uprange with the missing sector expressed by distal rays. Extrapolating the rays back to the crater locates the position of ejection. The difference between the focus of the sector boundaries and the crater rim provides a measure of uprange crater growth and collapse (Figure 28c).

Evidence for nonballistic emplacement, however, includes deflection around low-relief obstacles close to the rim (Figures 28d and 29a) and the multilobate patterns. Deflection of ejecta by a 300-m-high dome adjacent to the crater Seymour in Figure 29a indicates that the ballistic ejecta curtain must have collapsed soon after crater formation analogous to the laboratory experiments (Figure 23b). Radar-dark lobes extending farther from both craters are suggested to be analogous to observed flow separation and turbulent suspension of fines, thereby creating extended run-out flows beyond the bulk ejecta, as observed in the laboratory. These flows appear to leave very thin deposits since subtle preexisting relief remain visible, in direct contrast with the radar-bright ejecta.

The downrange emplacement process in Figure 29b is clearly modified by turbulent flow within a parabolic envelope that opens downrange. This downrange turbulent zone is also shown in Figures 17, 20b, 20c, and 21. Although the strong atmospheric blast rapidly dissipates downrange (Figure 16b), thermal effects and low pressures (and densities) persist to much later time (Figure 16c) and result in considerable interference with ballistic ejecta and melt flows deposited earlier near the rim.

The described sequence and style of emplacement are consistent with the atmosphere decelerating and entraining ejecta of all sizes as suggested by Schultz and Gault [1979]. Although small craters southwest (Figure 28a) and southeast (Figure 28d) of Carson might represent secondaries, they also could represent impactor fragments protected in the trailing wake of the major body. Evidence for atmospheric control is the slight curling downrange (Figure 28c) believed to represent redirection by strong draughting created as the principal atmospheric disturbance continues downrange. This redirection demonstrates that the bulk ejecta can be affected by aerodynamic drag.

Both examples in Figures 28 and 29 exhibit features characteristic of impact angles between 15° and 30° as indicated by laboratory experiments. Consequently, Figure 30a presents an additional illustration for a higher impact angle (>45°) based on the absence of an uprange ejecta avoidance zone. Nevertheless the sequence of emplacement is similar to the hummocky ejecta deposits draping lavalike run-out flows emplaced earlier (Figure 30b). The downrange rim is nearly devoid of the bright hummocky deposits but is characterized by smoother textured ejecta flows with featherlike termini. Radar-dark ejecta extend beyond the radar-bright deposits, but as around the other examples, the radar-dark deposits are relatively transparent to preimpact relief (ridges and fractures).

The atmospherically modified ballistic ejecta in Figure 30 not only exhibit the speckled hummocky inner deposits and distal radar-dark lobe but also a zone with intermediate radar reflectivity. This could be expressions of multiple stages of flow separation or entrainment with vapor. Radar-dark deposits streaking down the crater wall and mantling the ejecta suggest greater amounts of fallout of finer material, more pronounced uprange. The ballistic ejecta curtain from this higher angle impact would have directly intercepted and disrupted the westward winds aloft at late stages, thereby sustaining turbulence. Moreover, the late time fireball would have been carried westward by these winds, resulting in extensive fallout westward.

The featherlike termini occur downrange in this example (and in Figure 29b). This contrast in late stage emplacement styles with Carson can be interpreted through analogy with laboratory experiments and general behavior of turbidity flows [Schultz, 1992b]. In both analogs, highly turbulent debris flows develop nearly identical featherlike termini as the turbulent power can no longer support run-out. The turbidity flows in Figure 30 could develop from greater mixing between ejecta and the downrange vapor phase due to the higher impact angle. Such interactions are indicated by divergence of flows downrange. The coalescence of some networked flows into lobate-bordered emplacement styles suggest a progressive change from turbulent (nufes-ardentes-like) to laminar (lavalike) emplacement style. A similar sequence was shown in Figures 26 and 29. The possible significance of these contrasting and evolving styles of long run-out flows will be considered in more detail in the following section.

The 170-km-diameter crater Isabella in Figure 31 reveals considerably more complexity in crater shapes and ejecta facies at much larger scales. Lobate ejecta to the north and northeast are mantled by a radar-dark component. Ejecta flows extend about a crater diameter from the crater rim as indicated by disappearance of preimpact relief. The raised rim and wall region in the northwestern half apparently have been removed by collapse. To the south, the wall region remains exposed primarily because it intersects a 0.8-km-high relief (Figure 31b). The long run-out flow to the southeast seems analogous but is the result of redirection and channelizing by downrange topography (recall Figure 29). This particular example is included in order to show the effect of topography in dramatically changing overall appearance without changing the fundamental processes of early time downrange run-out flows and late stage ballistic ejection but nonballistic emplacement.

Figure 32 provides simplified terrain maps for direct comparison been emplacement sequence and styles shown in Figures 21, 24, and 30. These maps are not geologic maps but delineate contrasting modes of emplacement as a function of time. In spite of the wide range in sizes, very similar histories are exhibited. Although the run-out distance of the bulk ejecta decreases with increasing crater diameter, occurrence and extent of the turbulent or laminar-style run-out flows appear to depend on both crater size and impact angle. These two observations are documented in Figure 33. The degree of atmospheric interactions expected on Venus results in run-out of the atmosphere-entrained ballistic ejecta scaled to crater radius decreasing as R-1/2 (equation (11a)) as shown in Figure 33a. Following flow separation, the density of the ejecta flow approaches the density of the atmosphere. The resulting ejecta-entrained turbulent run-out flow is now expected to extend to a constant fraction of crater size (equation (11b)). These results are based on the assumption that the turbulent power is created only by the motion of the ejecta curtain. The former should correspond to the radar-bright inner deposits; the latter, to the radar-dark outer lobes. Greater run-out distances are expected if additional energy is introduced, e.g., potential energy due to greater slopes or internal energy due to entrained high-temperature vapor. The decrease (or constant) ejecta run-out on Venus yet increase in ejecta run-out for rampart-bordered flows around craters on Mars reflects the difference in ejecta entrainment. On Mars, ejecta entrainment increases with crater size (increase in ejecta velocity) and is affected by lithology.
Fig. 30. Ejecta emplacement sequence and style from the 67-km-diameter crater Stuart (30.8°S, 20°E) formed by an impact from the southeast. Although the impact direction is the same as upper level winds, the parabolic pattern revealed in Figure 30a (CI-30S027) develops from the higher impact angle and size of the impact. The ejecta plume from large craters may directly disrupt upper level winds with radar-dark deposits representing fallout from turbulent eddies. Figure 30b provides a closer view that shows the contrast in emplacement style depending on location. Uprange and at right angles to the impact trajectory, the ejecta deposits form short, stubby lobate flows (LF) extending about a crater radius from the rim but surrounded by radar-dark flows extending an additional crater radius and burying preexisting fractures (DF). The lower reflectivity is interpreted as finer ejecta (<10 cm) entrained in a turbidity flow generated by separation of the boundary layer from the advancing ejecta flow closer to the rim. Downrange (left) featherlike termini (TF) superpose radar-bright lavalike flows. These deposits are interpreted as a more turbulent mode of emplacement created by the heated atmosphere downrange. The radar-bright flows are believed to be impact related and are consistent with downrange emplacement at early times.
Fig. 31a. Complex ejecta facies extending from the 170-km-diameter two-ring basin Isabella (30°S, 204°E). Ejecta from crater excavation to the southwest are interrupted by an 0.8-km-high edifice. Although ballistically ejected from the crater, ejecta form a debris flow near the rim. Large preexisting relief can create barriers that redirect and channelize the rim flows. Two 200-m-high hills to the south remain exposed, thereby establishing an upper limit to the ejecta flow thickness. The long run-out flows to the east seem anomalous but in fact are proportionally comparable to other downrange flows if thickness is controlled by viscosity rather than continuous effusion (e.g., Figure 29). Here topography has redirected and channelized the run-out into a major flow. The radar-dark pond to the south probably indicates a smooth-surfaced ponded unit of melt.

(ejecta size). On Venus, the dense atmosphere results in entrainment regardless of size or lithology, thereby reducing the run-out distance (equation (11)). The trend in Figure 33a for Venus does not extend to much larger scales because increasing rim collapse consumes near-rim ejecta.

The downrange run-out flows exhibit a very different style of emplacement and dependence on crater size. The run-out distance of these flows depends on impact angle and the local slope (contrasted in Figures 26, 29, and 30). The relative area represented by the run-out flow deposits increases approximately with the cube of crater diameter Figure 33b). This observation could indicate progressive tapping of internal sources, increased impact-generated melt (relative to crater excavation), increased mixing with late stage ejecta, or a decrease in cratering efficiency with increasing crater diameter. Because of the timing of emplacement as well as control of the long run-out flows by impact direction, the last three alternatives provide the most plausible explanation, as discussed in subsequent sections.

These examples establish important constraints on late stage ejecta emplacement processes. First, the inferred atmospheric interaction did not result in extensive ejecta fallback and fallout, just as in laboratory experiments [Schultz and Gault, 1982; Schultz, 1981, 1991a, 1992b]. In contrast with volcanic or above-surface chemical explosions, crater excavation results from mechanical response to the shock wave; that is, it is not driven initially by gas backpressures. This fundamental aspect of impact cratering keeps the ballistic ejecta curtain tied to the growing cavity until the crater has finished forming. Atmospheric recovery to this outward moving wall results in strong winds and turbulence behind the curtain that sustains outward transport and disrupts simple ballistic emplacement. Second, the ballistic ejecta wall moves

Fig. 31b. Topography for region around the crater Isabella shown in Figure 31a. Dotted outline indicates ejecta deposit boundary with solid arrows depicting the direction of the major fluid run-out flows. The 1.6 km elevation marks the edifice that rises 0.8 km above the adjacent plains and blocked the non-ballistic flow of ejecta (dashed line).
outward with velocities exceeding 100 m/s, thereby generating winds and turbulence at least comparable in magnitude. As a result, the inner ejecta deposits should be extensively scoured by trailing recovery winds that can carry 1-10 m blocks and finer debris. Such winds would never again be achieved locally unless created by a subsequent impact nearby. This process is observed in the laboratory and was suggested to be responsible for contrasting erosional rates of ejecta facies on Mars [Schultz, 1991c]. Here it provides an explanation for the curiously well-preserved appearance of crater ejecta on Venus noted by Arvidson et al. [1991]: inner deposits composed of enormous size ejecta and lag surface. A corollary to this
due to turbulent mixing with the dense atmosphere, scouring of
from the crater, nonballistic basal ejecta flows (radar-bright)
exhibits atmospheric effects consistent with processes
60' from the horizontal, this should be a common occurrence.
appears that the early time processes become largely decoupled
fractions in the longer run-out flows should be a more sensitive
ejecta need not indicate a young age. Disappearance of the finer
conclusion is that the well-preserved state of the radar-bright
emplacement and crater formation on Venus

Fig. 33. Comparison of run-out of excavated ejecta (Figure 33a) and fluidized flows
(Figure 33b). Late stage ejecta flows exhibit crater-scaled run-out distances from
the rim decreasing as $D^{-1/2}$, consistent with nonballistic flow where density of the
flow approaches a constant fraction of atmospheric density (Schultz, 1992b). Circles
indicate two-ring basins which have undergone significant rim collapses, thereby
reducing the measured run-out distances. Run-out distance is referenced to the rim,
rather than crater center, based on the belief that the flows originate after ballistic
expulsion. Figure 33b compares the relation between flow area and crater diameter
for the long run-out flows. Flow area increases as $D^3$ for most craters, excepting
very high- and low-angle impacts (indicated by crosses and parentheses,
respectively). Such a relation is expected if flow thickness increases
with projectile mass for a constant flow thickness. A constant flow thickness would
be expected for a highly fluid flow.

inner ejecta
MARS
Mercury
Moon
 galer

Eddy-Suspended Flow
\[ \rho_e \gg \rho_a \quad \text{outer ejecta} \]
Air-Entrained Flow
\[ \rho_e + \rho_a \]
Venus

low impact angle

Log (FLOW AREA, km²)

5.0

4.0

3.0

2.0

10

100

0

1

10

100

10

100

Fig. 33. Comparison of run-out of excavated ejecta (Figure 33a) and fluidized flows
(Figure 33b). Late stage ejecta flows exhibit crater-scaled run-out distances from
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respectively). Such a relation is expected if flow thickness increases
with projectile mass for a constant flow thickness. A constant flow thickness would
be expected for a highly fluid flow.

high impact angle

Impact-controlled run-out flows. Impact melts associated
with terrestrial craters generally exhibit only traces (parts per
million or only trace element signatures) of the impactor. The
one exception is East Clearwater Lake, whose impact melt
contains an impactor signature approaching 8% in significant
contrast with only trace element levels contained in the
adjacent West Clearwater Lake melts [Grieve et al., 1980]. This
anomalously high percentage (and East Clearwater itself) has
been recently suggested to be a result of the West Clearwater
Lake impactor ricocheting and impacting downrange [Schultz
and Gault, 1991b]. Such a scenario closely parallels the
exploration of the adjacent, downrange depressions
recognizable not only on Venus (Figures 21 and 28c) but also
on other planetary bodies (Schultz and Gault, 1991a). While the
atmospheric density on Earth is insufficient to restrain either
the impactor ricochet or the vapor/melt from global dispersal,
the atmospheric density on Venus should have a profound
effect. Consequently, this section examines the working
hypothesis that the long run-out flows on Venus not only are
related to the early time, impact-generated vapor but also carry
a significant signature of the impactor, which would be lost in
other planetary settings.

The following discussion considers four tests. First, further
evidence for early time, impact-controlled flow and late time,
slope-controlled flow is considered. Second, the style of flow
should depend on impactor type: lavalike, laminar flows from
volatile-poor impactors (iron and silicate impactors); turbulent
flows for volatile-rich impactors (comets); and intermediate or
transitional styles for volatile-bearing or very high-velocity
silicate impactors. Third, the areal coverage of the flows should
depend on impact angle, and fourth, the mass represented by
all flows should not exceed a few projectile masses.

Impactor-controlled run-out flow at early time can be demonstrated by
examining the transition from trajectory to slope control of the
run-out path. Figure 34 shows the 36-km-diameter crater
Fussey that formed by an oblique impact on a northeast
trajectory and displays the same characteristic features noted in
Figure 2b: relatively symmetrical floor, slightly oblong shape
in plan perpendicular to the trajectory, radar-bright butterfly
lobes with distal radar-dark extensions, downrange ejecta
dispersal, and fluidized flow. The degree of wall slumping is
considerably less downrange due to a lower rim height, but
scars can be mapped beyond the rim region downrange.
Altimetry data (Figure 34b) confirm this downrange depression
and reveal that the regional slope is nearly perpendicular to the
trajectory. The run-out flow appears to originate in this
downrange depression but begins to follow the regional
gradient within a crater radius of the rim. This diversion
exposes a downrange stippled zone, which most likely
indicates the limit of the indirectly coupled atmospheric blast.
The slope calculated from the altimetry data is only 0.3°.
Consequently, the atmosphere effectively stopped the vapor
cloud within 40 km of the point of first contact by the
impactor. The high temperature and lower density of the
atmosphere resulted in a turbulent density flow that created a
network of parallel and coalescing flows that overrode low-
relief ridges.

If it is assumed that this flow initially averages about 10 m
Fig. 34. Transition from impact to slope control of a long run-out flow for the 30-km-diameter crater Fossey (2°N, 188.8°E; F00189). Missing sector of ejecta uprange characterizes oblique impacts and signifies direction (Figure 34a). Lobate ejecta extend to greater distances transverse to the trajectory and appear to curve around downrange zone. Local gradient (Figure 34b) diverts long, turbulent run-out facies and exposes a stippled semi-circular area consistent with effects of a downrange airblast. Size of this disturbed zone suggests an impactor 3 km in diameter (see text). If the long run-out flow averages 10 m in thickness, its total mass approximately corresponds to a projectile mass. The rim-out flow appears to emerge from a depression on the downrange rim indicated by narrower wall zone and suggested by altimetry data. Similar breaches of the downrange rim occur in other craters on Venus and other planets and are proposed to indicate effects of early time impactor ricochet and vapor blast. This example shows that slope control of run-out occurs within about a crater diameter of the impactor contact, consistent with calculations shown in Figures 14 and 15.

in thickness, then its area would suggest a deposit mass of the order of $10^{16}$ g (bulk density of 1.3 g/cm$^3$). The assumed thickness is based on the ability to overflow barriers. This can be compared with an impactor mass estimated from either the blast limit (equation (3b)) or from crater-scaling (equation (6a)). The 50-km-wide blast zone downrange yields a 3-km-diameter impactor corresponding to a mass of $3.5 \times 10^{16}$ g (density of 2.5 g/cm$^3$, $k = 0.5$, and $v = 30$ km/s). The crater-scaling relation gives a mass of $4.5 \times 10^{16}$ g for a 30 km/s object impacting at a 30° angle. As a further comparison, a vapor cloud that had expanded to about 7 km with a density of 0.1 g/cm$^3$ and a downrange velocity of 10 km/s would decelerate in the Venus atmosphere to sound speed within about 35 km (Figure 14a). Consequently, the mass in the flow is consistent to first order with the hypothesis that it largely represents the properties of the impactor.

Three other examples dramatize the effect of topography on redirecting run-out flows. Figure 35a illustrates a 64-km crater occurring on a 0.135° slope uphill from the inferred impact direction (indicated by the zone of avoidance). The flow appears to stagnate 40 km from the downrange rim and spreads laterally between wrinkle ridges before redirected downhill. Figure 35a also reveals that the uprange ejecta turn uphill consistent with interaction with strong draughting created as the impactor wake and vapor cloud continue downhill. Figure 35b shows the 28-km-diameter crater von Schuurman on the flanks of a large volcanic edifice. A radar-bright flow is visible through the downrange (upslope) ejecta deposits and has not been deflected. The flow appears from beneath the deposits as it continued downhill. It was clearly initiated downhill and largely emplaced prior to ejecta arrival.

The example (48 km in diameter) in Figure 35c also was formed by an impact directed uphill. The impact direction is less obvious but is indicated by the ejecta lobes uprange (downhill) and the disrupted facies downrange (uphill). The flows take three separate courses that cut and entrain ejecta as they veer downhill. Much longer turbulent flows appear to have overridden low-relief obstacles, eroded emplaced ejecta deposits and preexisting terrains, and ponded in valleys. These flows are consistent with slower moving mud-ardentes-like density flows that evolved from the fireball at later time. The extraordinary run-out distances on Venus may reflect additional turbulent power introduced to the flows as heat is released from phase changes (vapor to melt). The absence of engulfment of the crater floor indicates the complete decoupling of the ground-hugging density flow from later excavation and ejecta emplacement.

The run-out flows exhibit a wide range in emplacement
styles from laminar to turbiditylike run-out patterns. The laminar emplacement style around the un-named 89-km-diameter crater in Figure 36 is characterized by lavalike flows with lobate boundaries. These flows are sufficiently thick to overridden and mask underlying relief (ridges, fractures) closer to the crater but thin enough to be blocked by such relief near the termini. The viscosity of these flows is low enough to produce long run-outs and to fill in narrow fractures they override. Typically, such flows characterize the distal emplacement style and are fed by numerous coalescing flows nearer the rim. Central channels representing higher and more sustained flow velocities commonly appear to have fed the terminal, laminar run-out style.

A very different emplacement style is shown in Figure 37a. The 42-km-diameter crater exhibits many of the distinctive features of an oblique impact already discussed: slight uprange offset of the central peak and downrange disruption of lobate ejecta. The long run-out flow downrange is characterized, however, by overall transparency to the low-relief ridges and fractures it superposes. The flow boundaries exhibit enhanced radar brightening but become more diffuse with greater distance from the rim. Swirl patterns within the flow suggest considerable turbulence. Nevertheless, the flow exhibits interaction with the low-relief ridges in its continued course downrange.

The flow pattern displayed in Figure 37a indicates an emplacement style resembling a turbidity current. In laboratory experiments, such turbulence supports entrainment of coarser ejecta that are eventually deposited along the boundaries. A similar process would account for the radar-bright borders. In contrast with the laminar emplacement style, the area covered by the flow does not reflect the flow volume; rather, it indicates more where the flow has been. The long run-out occurs on an extremely low gradient (0.05'); therefore, it must be sustained by its own internal turbulent power, rather than a large slope.

The contrasting styles of emplacement are proposed to reflect contrasting volatile contents in the impact vapor cloud. The laminar-style flows are proposed to represent volatile-poor impact melt fractions coalesced from the decelerated and contained vapor cloud near the rim. The network of coalescing flows closer to the rim is suggested to indicate an earlier turbulent stage of the collapsing hot cloud. Many separate paths are possible as the cloud condenses from impact-driven dispersal downrange to slope-controlled run-out. The complexity of the network feeders should reflect the degree of downrange dispersal (impact angle), impact velocity (internal energy prior to coalescence), and local topographic complexity. In this scenario, it also may be possible to identify and characterize compositionally unique impactors through their emissivities, e.g., iron-rich asteroids producing radar-reflective flows with very low emissivities due to fractionation (high FeO). Higher impact angles will reduce the downrange kinetic energy component and result in mixing with ejecta either during launch or following near-rim emplacement.

By contrast, the turbulent emplacement style shown in
flows is their likely susceptibility to later erosion. Turbulent eddy velocities sustaining such flows need only be high enough to support the entrained debris. On Venus, terminal velocities even for 8 m blocks are only 60 m/s. Although considerably higher than ambient surface winds, atmospheric turbulence created by a later, nearby impact should easily attain such velocities. Arvidson et al. [1991] noted the problematic erosion of an ejecta flow associated with a 65-km-diameter crater in the "crater farm" (Figure 37b). They related the streaks crossing the region to the dark parabolic pattern enveloping the more recent crater Carson to the east (Figure 24). As suggested above, the expanding vapor cloud moving downrange from Carson should interrupt and divert upper level winds. As pressures equilibrate in the fireball, the residual thermal turbulence should be carried westward by the winds aloft. The wind-eroded ejecta flow (Figure 37b) noted by Arvidson et al. [1991] resembles the turbiditylike flows shown in Figure 37a and could be understood if downwind turbulence generated by Carson exceeded the turbulent power in the flow that originally created the flow deposit. The radar-bright borders of the eroded flows could indicate larger size fractions carried to the termini or welded material that would be more difficult to remobilize.

Several craters on Venus exhibit both a turbulent and laminar emplacement style of long run-out flows as illustrated in Figure 38 (also see Figures 26, 29, and 35c). The overview (Figure 38a) demonstrates the contrast in appearance between the lobes of near-rim ejecta and the topographically controlled sheetlike flows but also reveals three radar-bright flows. Figure 38b provides a closer view of these deposits and reveals that the radar-bright lobes emerge from networked and filamentary turbiditylike flows partly blocked by low-relief ridges. Such a sequence and pattern are consistent with hot density flows collapsing from the downrange fireball. As these turbulent flows decelerate at the ridges, dispersed melt coalesces to form very low-viscosity laminar flows. Because there is no effusive vent, the flows broaden downslope as they decelerate. The high density and relatively low melting temperatures of iron-bearing minerals from the impactor (or target) would be expected to fractionate from such a cloud. Further studies of both fractionation processes within hot vapor clouds and the radar characteristics of such examples on Venus are needed to test such a suggestion.

The characteristic emplacement styles around 253 craters larger than 30 km in diameter are shown in Table 4. If the turbulent emplacement style reflects the general absence of melt fractions that can coalesce to form coherent flows under the pressure/temperature conditions on Venus, then at least 58% of the craters were asteroidal and 42% cometary, a mix consistent with estimates suggested by Hartmann et al. [1981].

**Effect of impact angle.** The contrast in run-out distance and the areal coverage for similar size craters shown in Figures 26 and 30 suggest that impact angle plays an important role. Figure 39 provides direct comparison of selected 70-km-

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**Fig. 35. (Opposite) Timing and evolution of long run-out flows from oblique impacts.** Figure 35a (CI-00N009; +4°, 16°) shows a 64-km crater formed by an impact from the southwest. Altimetry data demonstrate that the impact direction was upslope, consistent with redirection of the downrange run-out flow by non-gravitational forces. Uprange ejecta curve around as a consequence of draughting by the downrange moving vapor cloud and impinging uprange wake from the impactor. Figure 35b (S7°, 191°; CI-00N197) shows the 28-km-diameter crater von Schuurnan with a radar-bright flow visible through the excavated ejecta deposits, thereby indicating downrange run-out redirected by the local slopes prior to ejecta emplacement. Figure 35c (F53N237; +75.1°, 241.5°) illustrates a 48-km-diameter crater formed by an oblique impact directed uphill on the flanks of a large volcanic edifice. Turbulent-appearing run-out deposits (T) extend to the northeast (A), are redirected downhill (B), cut across distal crater ejecta (C), and pond as thin units in valleys (D). Lavalike (L) melt flows extending to the south are superposed by ejecta. Both deposits emerge from a downrange disrupted zone (arrows). This contrast in timing between run-out and ejecta arrival is suggested to be a consequence of path length. The contrast in style may reflect the distinction between impact melt fractions that separated from the vapor cloud early and ground-hugging density flows that subsequently evolve from the residual debris in the fireball. Heat released as melts condensed from vapor phase may have produced additional ground-hugging turbidity flows extending from the lavalike melt flows.
diameter craters formed at progressively decreasing impact angles in order to underscore this point. The exact angle of impact for the example in Figure 39a is unknown, but the extension of ballistic ejecta lobes to the northwest and southeast, reduced run-out southwest, fluidized run-out northeast, and brightening of the preimpact terrain to the southwest all indicate an oblique impact from the southwest. The absence of an uprange zone of ejecta avoidance, however, suggests an angle approaching 45°. The greater asymmetry in ejecta deposits in Figure 39b (Figure 26), however, indicates a lower impact angle (20-30°). The 75-km-diameter crater in Figure 39c formed at an even lower angle from the southeast: southeast zone of avoidance; northwest and southeast extended ballistic ejecta lobes; northeast fluidized near-rim ejecta; radial bright/dark lineations beyond the ejecta that converge on the northeast rim; depressed northeast rim; and central peaks offset to the southeast. The absence of a central medial ridge and clearly elongate shape downrange require an impact angle higher than 5°-10°. Hence the impact angle is inferred to be about 15°. The last example (Figure 39d) is an elongate groove [Schultz, 1992c] that closely resembles grazing impacts (<5°) produced in the laboratory [Gault and Wedekind, 1978] and on the planets [Schultz and Lutz-Garihan, 1982; Schultz and Gault, 1990a]. These four examples document the effect of impact angle on the extent and coverage of the run-out flows.

Figure 40 provides closer views of the lower angle impacts in Figure 39c and d. In Figure 40a, the fluidized deposits extend over 350 km from the northeast rim, yet underlying ridges and fractures remain visible except through thicker lobes. Small extensions along narrow fractures indicate channelized flows with very low viscosities. Consequently, the large coverage by the flow actually corresponds to a veneer of debris left in its course. The impressive traverse reflects in part the angle of impact but also results from the impact striking near the summit of a volcanic edifice, thereby enhancing flow. The example in Figure 26 (Figure 39b) also showed the turbulent emplacement style near the rim, transparency to underlying relief and features, and deflection around small volcanic domes.

A closer view of the grazing impact in Figure 39d is shown in Figure 40b. The oblong shape (91 x 45 km) is very similar to large oblique impacts on the Moon (Schiller) and Mars (Orcus Patera) as discussed elsewhere [Schultz and Gault, 1990a, 1991a]. The example on Venus, however, exhibits two differences: the downrange rim is breached by a narrow gash, and fluidized deposits downrange create a complex pattern of flows. The fluidized run-out deposits emerge from the crater downrange and extend perpendicular from the gashlike extension. A radar-dark (smooth) pond occurs 250 km downrange (referenced to the uprange rim) and appears to be fed in part from flows that return toward the crater. Altimetry data (Figure 40c) reveal that this smooth-ponded unit occurs in a local depression and that the southernmost deposits are on an uprange-facing slope of a high ridge (0.9 km above the impact).

The crater bears striking resemblance to very low-angle (<5°) impacts produced in laboratory experiments [see Gault and Wedekind, 1978]. Even altimetry data reveal a gradually shallowing profile along axis from 350 km to 110 m downrange in direct analogy. At such angles the impactor literally decapitates with decreased disruption while maintaining a large fraction of the original impact velocity [Schultz and Gault, 1990a, 1991a]. Portions of the decapitated impactor reimpact...
Fig. 38. Composite run-out flows indicating both turbulent (networked flow pattern, N) and laminar (L) style emplacement processes emerging downrange from the 40-km-diameter crater (17°N, 147°). The overview in Figure 38a reveals the impact direction from the south. The closer view in Figure 38b shows that ridges in the preimpact surface partially blocked downrange/downdip flow from which the laminar-style flows emerge. This transition in styles is believed to indicate reassembly of denser melt fractions from a superheated impact vapor/melt density cloud as it was decelerated by the ridges. The high radar reflectivity could indicate selective fractionation of FeO from the impactor into the melt, thereby affecting the dialectic properties and radar emissivity.
at hypervelocities to form long gouges, whereas other portions ricochet off the surface. These processes appear particularly relevant for the example in Figure 40b with the added effect of the dense atmosphere.

The downrange ballistically controlled phase is much greater in Figure 40b than in other examples and seemingly in conflict with the effects of aerodynamic drag. This paradox can be readily understood in the context of laboratory experiments. At slightly higher angles the vapor cloud entrains ricochet debris and expands but is rapidly decelerated in the dense atmosphere of Venus. At lower impact angles, both vapor production and impactor disruption decrease as 80-90% of the impactor energy is retained in kinetic energy of the impactor [Gault and Wedekind, 1978; Schultz and Gault, 1990a]. The downrange debris stream reduces the rate of deceleration (see Figure 5a). As portions of this debris impacted the uprange-facing ridge, the resulting ricochet, melt, and debris were rapidly condensed and interacted with the trailing ricochet wake, after which local slopes controlled flow direction. Consequently, the smooth-ponded unit collected melt not only from collapse of this turbulent cloud uprange but also from return flow downrange.

Portions of the ricocheted debris in Figure 40b, however, appeared to survive impact. Although the 0.9-km ridge to the south formed an effective ballistic barrier, a radar-dark streak with radar brightening occurs farther downrange as elevations approach the height of this ridge. This radar-dark streak corresponds to a region of anomalously low emissivity (0.74) near -12', 9'E (shown by Tyler et al. [1991] and by Campbell et al. [this issue]) extending 1500 km downrange from the impact. These observations suggest that hypervelocity ricocheted impactor debris left the crater at angles of only a few degrees (sufficient to clear the downrange ridge). The atmospheric shock from this exiting debris created a radar-brightened zone on the rise farther downrange with reentry ablation products and fallout producing a low-emissivity signature of its continued downrange trajectory.

The absence of a well-defined radar-dark parabola associated with this low-angle impact is also consistent with a debris stream of ricocheted debris. Even though impact direction and size should favor formation of the parabola pattern, the energy partitioned to both the target and impactor decreases dramatically for impact angles lower than 7.5' [Gault and Wedekind, 1978; Schultz and Gault, 1990b]. Reduced vaporization should minimize blast standoff and upper winds. Moreover, the ricochet debris stream may become collimated, rather than dispersed (see Figure 4) with reduced drag (Figure 5a). Nevertheless, a broad low-emissivity region occurs westward from the end of the inferred ricochet trail and may indicate dispersal and fallout from the westward winds aloft.

The sequence in Figure 39 and the extreme case in Figure 40b provide further support for the hypothesis that the fluidized run-out flows are driven if not directly related to the impactor. The downrange run-out could not simply represent ballistic ejection from crater formation since drag would limit the range and since such ejecta would be emplaced on either side of the elongated crater. On the Moon and Mars, similar direct evidence of the impactor at such low angles is lost completely due to the underdecelerated high ricochet velocity which greatly exceeds the escape velocity.

Figure 39 clearly demonstrates the increase in areal coverage of the run-out flows with decrease in impact angle. The visual impression, however, is that the mass in such flows might exceed the mass of the impactor, if not the excavated crater mass. This impression leads to the last of the four tests posed in the preceding subsection: the mass represented by all flows should not exceed a few projectile masses. Run-out flow mass can be simply calculated from the areal coverage multiplied by an assumed thickness. Deflection of the flows by wrinkle ridges and containment within narrow fractures help to constrain the thickness. The minimum relief for the ridge and fractures is limited to about 5 m since they are resolved with the relatively long-wavelength radar. The maximum relief is set by their not being resolved in the altimetry data (<50 m). On the basis of very similar ridges on the Moon and Mars, they are most likely less than 20 m in height. Although the long runout flows exhibit thickness variations along their length, they are generally very similar, whether associated with a crater 40 km or 100 km in diameter. This result might be expected if all flows result from very high initial temperatures due to an impact. With these considerations, a working value of 10 m is adopted with full cognizance that this could underrepresent deposits from turbidity flows yet underestimate distal laminar-style flows.

The corresponding mass of the impactor forming the crater is calculated in two ways. First, equation (6), which is based on laboratory experiments, can be inverted to calculate impactor mass directly for a given velocity and density. From comparisons with estimated impactor sizes from atmospheric blasts (discussions with Figures 10 and 12), however, this approach might underestimate projectile mass. Consequently, a second approach extrapolates only from the minimum crater-forming body surviving atmospheric entry, that is, impactor size corresponding to the maximum craterless haloes (from...
butterfly-type ejecta patterns but without a missing uprange sector can be classified as low-angle impacts (15'-25'). Craters the correlation with estimated run-out flow mass. More increases as impact angle decreases, and Figure 43a confirms diagnostic clues as summarized in Figure 42. Craters exhibiting be estimated precisely but can be qualitatively distinguished by mass can be demonstrated in two ways. Impact angles cannot such a zone are classified as very low impact angles (probably of the uprange zone of avoidance and other exception of two craters formed by impacts at higher angles.

The effect of impact angle on the estimated run-out flow mass can be demonstrated in two ways. Impact angles cannot be estimated precisely but can be qualitatively distinguished by the presence of the uprange zone of avoidance and other diagnostic clues as summarized in Figure 42. Craters exhibiting such a zone are classified as very low impact angles (probably less than 15'). The angle subtended in the missing sector increases as impact angle decreases, and Figure 43a confirms the correlation with estimated run-out flow mass. More generally, higher-angle impacts exhibit progressively decreasing asymmetry in the ejecta pattern. Craters with the butterfly-type ejecta patterns but without a missing uprange sector can be classified as low-angle impacts (15'-25'). Craters with an asymmetric ejecta pattern characterized by slightly shorter uprange and greater downrange ejecta lobes are termed medium-low impact angles (25'-45'). Symmetrical ejecta patterns are obviously classified as high impact angles. These four classifications prove adequate to confirm increasing run-out flow mass with decreasing impact angle (Figure 43b).

Summary. The styles and sequence of ejecta emplacement on Venus largely reflect three very different and temporally separate interactions with the atmosphere. Preimpact failure of the impactor or the ricochet process results in a downrange vapor/melt cloud expressed by a variety of signatures downrange: shallow depression indicating collision with the ricocheted impactor prior to dispersal, a blast center offset on the downrange crater rim, disruption of downrange ejecta emplacement, and long run-out flows sustained by turbulent power. Supporting evidence for this interpretation includes increased run-out with decreased impact angle, initial run-out direction controlled by impactor trajectory, mass comparable to a projectile mass, and emplacement prior to arrival of crater-excavated ejecta. The long run-out flows are proposed to indicate density flows collapsing within the evolving vapor cloud due to the reduced pressures. The contrasting emplacement styles may reflect different impactor types: turbidity flows transparent to underlying topography due to volatile-rich impactors (comets) and laminar, lava-like flows indicating silicate and metal-rich impactors (asteroids). Deposits from cometary impacts result in sustained flows due to the volatile content and should be more susceptible to subsequent erosion. Further refinements to impactor identity may be possible by careful comparisons of inferred turbulent power, emissivity, and backscatter characteristics.

Later stages of ejecta emplacement are largely decoupled from the early time blast. As a result, ejecta from crater excavation fully interact with the atmosphere, except downrange in an oblique impact. The outward moving ejecta curtain creates intense turbulence that scours the inner ejecta deposits and creates radar-dark ejecta turbidity flows of entrained finer debris that overrun the inner rim. It is suggested that the intensity of this scouring creates a lag surface that is stable against long-term aeolian reworking unless directly affected by a later nearby impact. The outer radar-dark flows, however, represent the smaller size fractions removed from the inner facies and may be lost through time. The general absence of masking by extensive fallback within the crater underscores the importance of outward moving turbulent winds. At very late stages, the more slowly evolving turbulent fireball collapses into turbidity flows along the surface but expands above. The ground-hugging density flows create strong recovery winds behind them and can entrain previously emplaced ejecta. Aloft, the fireball undergoes runaway expansion driven by the decreasing density with altitude similar to the model described by Jones and Kodis [1982] for strong terrestrial explosions. The radar-dark parabolic pattern reflects interactions between the downrange moving blast and upper level easterlies.

The sequence of emplacement between the run-out flows and ejecta establish constraints on the relative times of arrival. Table 5 illustrates this approach. A run-out flow traveling from the downrange rim "source" region to the point where it emerges from below the ejecta deposits is estimated by dividing this distance by an assumed flow velocity. For a minimum time, the velocity is assumed to be 100 m/s. The minimum time required for the ejecta to reach this position $T_1$ is calculated by combining the time to form the excavation cavity ($T_{ce}$, equation (6b)) with the ejecta ballistic travel time $t_b$ without any deceleration due to drag. Consequently, this also provides a lower limit. Table 5 reveals that $t_b >> T_1$. This is inconsistent with the geologic evidence for the examples in
Fig. 40b. A closer view of the very low-angle impact introduced in Figure 39d. Such low-angle impacts result in decreased melt/vapor generation as significant fractions of the impactor ricochet downrange with a large fraction of the original impactor energy remaining as kinetic energy. This observation based on laboratory experiments is consistent with the extended downrange run-out uphill, as indicated by the accompanying profile from the altimetry data (Figure 40c). The run-out flow extended 150 km downrange and 200 m uphill before cascading back into a ponded smooth deposit. This downrange run-out is consistent with a debris flow driven by and dominated by the impactor. The long radar-bright flows extending to either side exhibit a distinctly higher emissivity, whereas a broad region of low emissivity extends several hundred kilometers downrange.

Figures 24, 30, 35b, and 36 where the ejecta clearly arrive later. It is proposed that such an emplacement sequence is possible only if the ejecta were emplaced as flows following significant deceleration in the atmosphere. For purposes of illustration, the time for such ejecta flows to be emplaced \( (T_{em}) \) is estimated by assuming an outward flow velocity of 50 m/s for a 50-km-diameter crater and scaling according to \( R^{1/2} \). With these assumptions, ejecta arrival times now exceed flow travel times for all cases except the example in Figure 35c, where the total path length for this flow is unusually large because the downrange rim is upslope.

4. CRATER FORMATION

The evidence for the role of the atmosphere in shielding the surface from smaller impactors, in containing the early time vapor cloud, and in controlling ejecta emplacement leads to the issue of its possible role in affecting crater dimensions. The following discussion briefly reviews direct experimental evidence for atmospheric effects on crater scaling relations and considers diagnostic clues that might be found in the Venus cratering record.

Processes

Atmospheric effects on crater size and shape. Crater excavation in a vacuum occurs as an orderly process reflected in
Laboratory experiments do not simulate planetary-scale phenomena directly. Well-known scaling ratios, however, allow calibrating their effects and include the following: the Froude ratio, (ratio of inertia to gravity forces), Euler (inertial to viscous forces), and Reynolds Number (inertial to viscous forces). This approach involving matching force and density ratios can be formalized through dimensional analysis. For example, the $\pi$ groups controlling cratering in a vacuum [Holsapple, 1987] can be viewed as an inverse Froude Number for gravity-controlled growth (the $\pi_2$ parameter) or an Euler Number for strength-controlled growth. The advantage of dimensional analysis is the detailed tracking of exponents; the disadvantage is the assumption that all controlling or competing processes have been identified [Sedov, 1957]. The presence of an atmosphere introduces processes acting simultaneously over a wide range of scales [Schultz, 1992a and b]. The outward advance of the ensemble of ejecta comprising the ejecta curtain represents one scale, whereas aerodynamic drag acting on individual ejecta represent another. Different scaling ratios may be necessary for different phenomena. Observations of processes in laboratory experiments help to identify their signatures in different planetary environments.

Fig. 41. Comparison of calculated mass in run-out flows with size. The run-out flow mass is calculated on the following first-order assumptions: an average thickness of 10 m controlled by viscosity rather than supply; a deposit density of 1.5 g/cm$^2$, and no dependence on impact angle or style of emplacement. Such assumptions will result in an underestimate of impactor mass for laminar emplacement styles and high impact angles (less run-out). Run-out mass is plotted as a function of impactor mass calculated from equation (6) for a common impactor velocity (28 km/s) and density (2.5 g/cm$^3$) shown on the lower abscissa; extrapolation from the cratering limit (Figure 11b) using the exponents from equation (6) is shown on the upper abscissa. No correction for impact angle has been included in the scaling relation. As expected, higher-angle impacts exhibit less run-out consistent with either an underestimate of flow thickness or neglect of impact angle in deriving impactor mass. Very low grazing impacts (crosses) provide a constraint on impactor mass if the run-out is dominated by ricocheted impactor products. The larger example (Figure 40b) is shown with an assumed thickness of 20 m suggested by burial of preexisting relief. The use of direct application of equation (6) suggests that the impactor comprises about 10% of the run-out flow mass. Use of the cratering limit (upper abscissa), however, suggests that the run-out flow is dominated by the impactor, as consistent with limited data for downrange run-out from grazing impactors. In either case, the derived run-out flow mass appears to be directly proportional to projectile mass (excluding high-angle impacts).

Fig. 42. Diagnostic signatures of impact angle and direction based on laboratory experiments [Gault and Wedekind, 1978] and craters on the Moon and Mars. Very low impact angles (<10° from horizontal) result in an oblong shape created as the impactor transfers its energy along the trajectory. Crater depth in simple craters is deepest uprange resulting in steep uprange and shallow-sloping downrange walls. The basin-like shape of craters on the Moon and Mars (as well as laboratory experiments) is displaced downrange on Venus, perhaps due to strong winds drawn downrange by ricocheted debris. Long run-out flows cover the broadest areas and extend the greatest distances downrange (Figure 38) unless redirected by slopes (Figures 34 and 35b). Impact angles between 10° and 20° produce craters oblong transverse to the trajectory. Failure of the rim/wall uprange due to oversteepening and the shallow-sloping downrange wall commonly results in a heart-shaped floor boundary. In complex craters, the central peak or peak ring is typically offset uprange unless the crater outline is modified by more extensive rim/wall failure uprange. Peak rings commonly are open downrange. Ejecta deposits are typically missing uprange unless the crater outline is modified by more extensive rim/wall failure uprange. Peak rings commonly are open downrange. Ejecta deposits are typically missing uprange unless the crater outline is modified by more extensive rim/wall failure uprange. Peak rings commonly are open downrange.
The effect of impact angle as a function of the uprange zone of missing ejecta (sector angle) reflecting impact angle (Figure 42). The observed decrease in run-out mass with decreasing sector angle (increasing impact angle from the horizontal) is consistent with impactor-dominated run-out flow. Figure 43b tests this hypothesis further by grouping selected data sets into different impact angles following criteria shown in Figure 42. Decrease in run-out flow mass with increasing impact angle indicates increasing vapor/melt production and entrainment with decreasing impact angle, an impact angle dependence on the derived impactor mass, and/or greater loss of vapor/melt by injection into the upper atmosphere.

While observations of the planetary crater record allow assessment of the relevance of laboratory (or computational) experiments. This is the approach applied here for the first-look analyses of the Magellan crater record. The formalism developed by Holsapple and Schmidt [1982, 1987] provides an important framework for interpreting the cratering experiments. Impact-cratering efficiency for targets controlled by gravity under vacuum conditions can be given by

\[ \pi v_0 = k' \pi_2^{-\alpha} \]  
\[ \pi v_0 = k'(3.22 \text{ gr}\text{/v}^2)^{-\alpha} \]  

where \( \pi v_0 \) is the cratering efficiency defined as the displaced target mass divided by the impactor mass, \( k' \) is an empirical constant dependent on target properties, \( g \) is gravitational acceleration, \( r \) is projectile radius, \( v \) is impact velocity, and \( \alpha \) is an exponent that depends on the transfer of impactor energy and momentum to the target at the earliest times [see Holsapple and Schmidt, 1987]. Introduction of an atmosphere results in both ambient pressure and gravity controlling crater growth. The relative reduction in cratering efficiency (hence reduction in crater diameter) can be expressed by dividing the observed efficiency in an atmosphere \( \pi v_A \) by the expected efficiency in vacuum \( (k' \pi_2^{-\alpha}) \):

\[ k \pi_2^2 \pi v_A = \pi v_0^B \]  
\[ k \pi_2^2 \pi v_A = [P/\delta p^2 \pi_2^2 \pi v_A^2]^{-B} \]  

where \( k = 1/k' \) and the dimensionless pressure parameter \( (P/\delta p^2 \pi_2^2 \pi v_A^2) \) introduces pressure \( P \) and target density \( \delta \) for crater growth controlled by both pressure and gravity [see Schultz, 1992a]. The role of atmospheric pressure in this case resembles the effects of strength \( Y \) in the dimensionless expression \( Y/\delta p^2 \). Note that equation (13b) includes the \( \pi_2 \) term that increases with increasing impactor size; consequently, cratering efficiency (crater size) should seem to decrease for craters smaller than the transition from pressure to gravity scaling.

The effect of atmospheric density was separated experimentally from the effect of pressure by contrasting the effects of helium and argon (or carbon dioxide) atmospheres. For sufficiently small ejecta or sufficiently high atmospheric densities, the ejecta curtain angle steepens during crater growth and becomes distorted at late times [Schultz, 1992b]. The observed role of atmospheric density and particle size (as well as particle density) in ejecta curtain angle indicates that viscous drag also plays a role in crater growth at laboratory scales. If drag forces \( (d) \) exceed gravity \( (g) \) forces, then cratering efficiency referenced to vacuum conditions is expressed by

\[ k \pi_2^2 \pi v_A = [(P/\delta p^2 \pi_2^2 \pi v_A^2)^B (d/g)]^{-\alpha} \]  

where the drag/gravity ratio is given by

\[ (d/g) = 1/(C_D \rho v_e^2 / \delta g a) \]  

Table 5. Comparison of Minimum Time for Ejecta Emplacement With Time for Run-out Flow Emplacement

<table>
<thead>
<tr>
<th>Example</th>
<th>Figure</th>
<th>Diameter, km</th>
<th>( T_c )</th>
<th>( t_b )</th>
<th>Time, s</th>
<th>( T_e )</th>
<th>( T_{fe} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carson</td>
<td>24</td>
<td>48</td>
<td>34</td>
<td>126</td>
<td>160</td>
<td>700</td>
<td>&gt; 500</td>
</tr>
<tr>
<td>Stuart</td>
<td>30</td>
<td>66</td>
<td>40</td>
<td>148</td>
<td>190</td>
<td>1070</td>
<td>&gt; 600</td>
</tr>
<tr>
<td>von Schuuman</td>
<td>35b</td>
<td>28</td>
<td>26</td>
<td>96</td>
<td>120</td>
<td>510</td>
<td>&gt; 400</td>
</tr>
<tr>
<td></td>
<td>35c</td>
<td>48</td>
<td>34</td>
<td>126</td>
<td>160</td>
<td>700</td>
<td>&lt; 800</td>
</tr>
<tr>
<td>Un-named</td>
<td>36</td>
<td>89</td>
<td>47</td>
<td>173</td>
<td>220</td>
<td>960</td>
<td>&gt; 600</td>
</tr>
</tbody>
</table>

\( T_c \) is crater formation time from equation (6b). \( t_b \) is time for ballistic emplacement at one crater radius \( R_0 \) from the present crater rim (no drag; ejection angle is 45°). The ballistic range is calculated from the excavation cavity and includes corrections (0.68\( R_o \)) for use of the apparent diameter and enlargement due to slumping (0.8\( R_o \)). \( T_e \) is minimum time for ejecta emplacement equal to \( T_c + t_b \). \( T_{fe} \) is time for nonballistic ejecta to reach one crater radius from the rim assuming a constant velocity of (5 m/s)(R/50 km)\( 1/2 \) from the excavation rim. Also includes time for crater formation. \( t_f \) is time for flow to reach from rim to edge of ejecta deposits with an assumed flow velocity of 100 m/s for illustration. This is most likely too high for typical lavalike flow driven by effusive pressures but may be appropriate for an evolving, hot turbulent flow.
Fig. 44. Effect of atmospheric pressure and aerodynamic drag on cratering efficiency (Figure 44a) and crater shape (Figure 44b) for different target materials based on laboratory experiments (from Schultz [1992a] and Schultz [1992b], respectively). Figure 44a shows the reduction in cratering efficiency (displaced mass relative to projectile mass) referenced to vacuum conditions as a function of a dimensionless scaling parameter including atmospheric pressure ($P$), impactor density and velocity ($\delta_i$ and $v_i$, respectively), the gravity-scaling parameter ($v_0$) and the relative role of drag ($d$) and gravity ($g$) forces (see text). Laboratory data indicate that both ambient and dynamic (drag) pressures affect crater excavation for targets exhibiting a wide variety of material properties (internal angles of friction from 20° for microspheres to 80° for pumice) and average grain sizes (450 µm for 24 sand, 120 µm for 140-200 sand, 80 µm for pumice, and 100 µm for low-density microspheres). Such data indicate that the dense atmosphere on Venus might affect cratering efficiency. Comparison of forces acting to retard advance of the crater lip as a function of scale supports this possibility. Figure 44b shows the effect of an atmosphere on crater shape. The high internal angle of friction for compacted pumice targets preserves the transient crater profile, whereas sand targets undergo collapse immediately after excavation due to an oversteepened profile. Atmospheric pressure restricts lateral crater growth but does not modify crater depth; consequently, crater shape changes at the end of excavation. Because passage of the shock front disrupts the excavated material, such particulate targets provide a more realistic analog for large-scale impacts.

With the drag coefficient given by $C_D$, atmospheric density by $\rho$, and ejecta velocity, density, and size by $v_e$, $\delta_e$, and $a$, respectively.

Since ejection velocity at a given stage of growth increases with crater size, equation (14a) predicts a greater decrease in cratering efficiency with crater size than indicated by equation (13). Figure 44a illustrates application of this expression for a variety of targets in the laboratory. Because cratering efficiency is similarly reduced in particulate targets with both high internal cohesion (e.g., compacted pumice) and very low cohesion (micro-spheres), it was concluded that drag forces must control crater growth. In effect, $d$ replaces $g$ in $\pi^2$ term (equation 12b).

These three formulations can be greatly simplified for different planetary settings by introducing known values for gravity and by using an expected impact velocity based on...
orbital dynamics of the most likely impactor [see Hartmann et al., 1981]. If it is further assumed that the crater diameter can be simply derived from the cube root of the total displaced mass, then the following four expressions emerge for the same impactor/target density ratio: for gravity scaling,

$$D/2r = \left( \frac{r}{{2g}} \right)^{0.22}$$  \hspace{1cm} (15a)

for gravity-pressure scaling,

$$D/2r = \left( \frac{r}{{2g}} \right)^{0.27}$$ \hspace{1cm} (15b)

for pressure-drag scaling,

$$D/2r = r^{0.48} g^{-0.05}$$ \hspace{1cm} (15c)

and for drag scaling,

$$D/2r = r^{0.40} g^{-0.04}$$ \hspace{1cm} (15d)

where the exponents have been derived from \((\alpha/3) = \mu/(2 + \mu)\) with \(\mu = 0.55\) for nonporous targets [see Holsapple and Schmidt, 1987] and \(\beta = 0.23\) from experiments [Schultz, 1992a].

Laboratory experiments also show that the excavation crater changes shape as a function of atmospheric pressure [Schultz, 1990b]. Craters formed in targets with low internal angles of friction were found to collapse immediately after formation. As a result, the final crater profiles became shallower with increasing pressure and density. Craters formed in compacted pumice, however, retained the excavation profile and exhibited a progressive decrease in the ratio between diameter and depth, i.e., craters became more hemispherical. The much higher internal angle of friction for compacted pumice resulted in possible strength effects as \(n_2\) decreases, a minimum ejection velocity necessary to escape the cavity), \(V_e(t)\). For simplicity, the plate can be assumed to have a medium. Forces retarding advance of particles in the curtain preserved or witnessed. Figure 44b contrasts these changes in the transient crater shape (profile) in an atmosphere indicate that the excavation crater 

$$\ln(v_e) - C_{D} \left( \frac{L}{D} \right)^{1/2}$$ \hspace{1cm} (16b)

and predicts that the effect of dynamic forces on limiting crater growth should increase with increasing crater size. This conclusion may seem counterintuitive when the total ejected mass from the crater is compared with the total displaced mass of the atmosphere. It simply reflects, however, the contrasting effects of dynamic forces acting on a brick versus a thin plate, or more accurately, a debris sheet.

The expanding-cylinder analogy is an oversimplification for impact cratering at large scales. The assumption that the velocity and thickness of the curtain can be characterized by a constant dependent only on scale is clearly incorrect. Introducing a time dependence, however, should enhance the predicted effect: smaller mass per unit area with a higher outward velocity at early times. An implicit assumption is also made that the atmosphere is incompressible at ambient conditions, whereas Figure 22a indicates that ejecta curtain velocities should exceed the speed of sound during the early stages of growth. Since most crater excavation occurs at late times, however, this assumption should not be fatal.

The purpose behind reviewing the laboratory experiments and considering the simplified analogy is to demonstrate that crater dimensions on Venus may not be directly comparable to dimensions on other planets. In addition to future theoretical studies, observational constraints may be derivable from the cratering record on Venus through crater depth-to-diameter relations (Figure 44b) and possible signatures of impact dimensions (equation (15)).

The laboratory experiments indicate that the atmosphere affects the profile of the excavation cavity. If this profile creates walls/slopes exceeding the internal angle of friction, then rim collapse ensues. Nevertheless, the relation between the depth and diameter of the collapsed crater parallels the constant ratio characterizing craters formed under vacuum conditions (Figure 45a). Such a conclusion is consistent with previous discussions of rim/wall failure where the degree of collapse increases as a constant fraction of the excavation crater [Schultz, 1988c]. If these results extend to large scales, then crater shapes on Venus may not follow the gravity dependence observed for craters on atmosphere-free bodies [Pike, 1988; Schultz, 1988c]. If larger craters on Venus are systematically shallower than craters on the Moon, Mars, or Mercury principally due to crater enlargement, then the relation between depth and diameter should parallel the simple-crater relation (i.e., constant diameter/depth). Because other modes of crater collapse can produce similar results, however, the diameter/depth data cannot be considered diagnostic but only supportive. Figure 45a provides a summary of the possible expression of atmospheric effects on crater shape, while Figure 45b shows both the possible reduction in crater diameter due to reduced cratering efficiency and subsequent enlargement.

Direct application of the experimental results shown in Figure 44a to conditions on Venus (8-km-diameter body impacting at 28 km/s for an average ejecta size of about 30 cm) results in a value of -3.0 for the abscissa and predicts that a 40-km-diameter crater on Venus would have been 75 km in diameter without an atmosphere (rim-rim diameter including 25% enlargement by slumping). Such extrapolation over 5 orders of magnitude in scale is clearly precarious. Nevertheless, this is a useful exercise in order to show that cratering efficiency might be affected by the Venus environment.
Possible signatures of impactor size. If the atmosphere affects crater growth, then the early stages of impactor penetration and target compression should comprise a larger fraction of the final crater size as crater size increases or as impact angle decreases. The early time transfer of kinetic energy from impactor to target occurs within several projectile radii (e.g., Orphal et al., 1980). At later times, the cratering flow field for hypervelocity impacts responds with little "memory" of its initial source characteristics (i.e., large and low velocity or small and high velocity), which forms the basis for late stage equivalence (Dienes and Walsh, 1970). As projectile size increases, however, the minimum dimension characterizing energy transfer from impactor to target increases with decreasing impact velocity as illustrated in Figure 45. Consequently, the position $y$ where equation (17) becomes invalid increases with decreasing impact velocity $v$ and velocity $v$ into a target with a density $\rho_t$ and sound speed $c$. This expression only applies when $x$ is greater than a critical dimension $y$ incorporated in the coupling parameter given by $C = y \delta_1 \nu_2 \mu$, with the exponent $\nu = 1/3$ and $\mu$ ranging from 1/3 to 2/3 for momentum and energy scaling, respectively. Consequently, the position $y$ where equation (17) becomes valid increases with decreasing impact velocity as illustrated in Figure 46.

If a minimum dimensionless stress characterizes a common zone of displacement associated with the impactor penetration, then the corresponding dimensionless distance $x_o$ in projectile radii for a given impactor density is given by

$$x_o \sim \nu (v/c)^{\mu}$$  \hspace{1cm} (18a)

Conversely, projectile size might be derivable from this common reference dimension:

$$r \sim x_o (c/v)^{\mu}$$  \hspace{1cm} (18b)

Equation (18a) predicts that $(x_o/r)$ should be approximately constant on a given planet (that is, within a given range of impact velocities and target properties). Crater diameter scaled
produced by oblique impacts where the peak or peak ring is planetary surfaces. First, central peaks generally correspond to the region of initial energy transfer. This is indicated by craters impactor and central peak complexes is found on various enhanced collapse of the transient crater rim [Head, 1977]. signature of this impactor-scaled zone due to the additional Multi-ring basins, however, may not preserve a simple disruption zone similar to processes envisioned in previous studies with differing details in the specific mechanics [Greeley et al., 1980; Croft, 1981; Melosh, 1982; and Pike, 1983]. velocity impacts. Cntral rings may form from uplift of the central disruption zone as well as from collapse of the unstable central rebound. 

Dimensions of central peak rings and pits in craters on the Moon, Mercury, Mars, and Ganymede might provide a possible measure of \( x_o \) [Schultz, 1988c]. In the context of Figure 46, the physical expression for \( x_o \) reflects the difference between the maximum dimensionless peak stress created at impact and a limit \( (P/\delta_1 c^2)_{o} \) surrounding the impactor at maximum penetration. This stress limit still greatly exceeds conditions that eventually limit lateral crater growth. High impact velocities produce a shocked zone (including melted and vaporized material) much larger than the projectile (equation (18a)), whereas low impact velocities create a shocked zone only slightly larger than the impactor. With this perspective, central pits might represent a preserved imprint of lower velocity impactors, whereas central peaks reflect the target response (decompression and rebound) to a disrupted and vaporized/melted zone much larger than the impactor at higher velocities. Peak rings could develop from uplift of the central disruption zone for long penetration times characterized by very large (or low velocity) impactors [Schultz et al., 1981; Schultz, 1988c] and/or from collapse of the unstable uplifted disruption zone similar to processes envisioned in previous studies with differing details in the specific mechanics [Greeley et al., 1980; Croft, 1981; Melosh, 1982; and Pike, 1983]. Multi-ring basins, however, may not preserve a simple signature of this impactor-scaled zone due to the additional lithospheric response [Melosh and McKinnon, 1978] and enhanced collapse of the transient crater rim [Head, 1977].

Observational support for the proposed link between impactor and central peak complexes is found on various planetary surfaces. First, central peaks generally correspond to the region of initial energy transfer. This is indicated by craters produced by oblique impacts where the peak or peak ring is typically offset uprange, as in Tycho on the Moon, or the inner ring of Crisium [Schultz and Gault, 1991a]. Exceptions to this rule occur where rim/wall collapse is more extensive uprange (e.g., King crater on the Moon). Because oblique impacts produce a steeper slope uprange and lower slope downrange [e.g., Gault and Wedekind, 1978], greater uprange rim/wall collapse should be expected. Nevertheless, radial elements within the missing ejecta sector uprange invariably converge inside the precollapse excavation cavity. Second, overlapping craters formed by simultaneous impacts on Mars and Ganymede each exhibit separate central pits [Schultz, 1988c]. And third, central pits and peak rings in craters formed by oblique impacts typically are breached downrange with extensions indicative of progressive impactor failure during target entry, as in Bach on Mercury or King on the Moon [Schultz and Gault, 1991a]. Analogous signatures exist on Venus as summarized in Figure 42.

If the size of the central peak complex (peak, pit, or ring) in a crater is proportional to \( x_o \), then equation (18b) can be used to estimate impactor size for the expected rms impact velocity for asteroids and sound speed in the upper planetary crust. Figure 47 reveals that the observed slope is consistent with expectations from equation (15a) for each planet and merge in a single line for a given peak type for reasonable values of impact velocity and sound speed. The central rings/pt data are slightly offset above central peaks and two-ring basin data. This should be expected since the rings/pt data are referenced to their summit relief rather than their base as done for central peaks.

In summary, the dimensions of central peak complexes are proposed to be measures of impactor size by indicating a common stress limit but different responses depending on impactor velocity (difference between peak stress and a common stress limit for silicate targets). Moreover, the
relative size of the central peak complex should become larger as impact angle decreases as depicted in Figure 42. The wide range in central peak morphologies and inferred impact angles on Venus allows testing this proposal. If the atmospheric pressure also affects crater scaling, then the relative size of the central peak should be predictably different (equation 15).

**Venus**

**Impact angle effects.** The atmosphere of Venus enhances the diagnostic features of oblique impacts and allows characterizing changes in crater morphology with scale at a given impact angle, as well as examining changes at a given diameter for different impact angles. Six different crater sizes containing central peak rings are shown in Figure 48. The smallest example (36 km in diameter, Figure 48a) exhibits the typical elongate shape of the peak ring and the characteristic offset uprange with respect to the crater floor. The uprange zone of ejecta avoidance forms a sector truncated by the crater rim, and extrapolated ejecta lineations form an apex of the missing sector converging inside the crater rim. For ballistically ejected debris, the offset inside the rim can be used as a measure of crater enlargement uprange from the transient rim, in this case about 25%. The slightly larger 50-km-diameter crater Cunitz (Figure 48b) exhibits a central peak ring that is breached downrange and more clearly offset uprange. The crater floor forms a small scallop uprange where the crater wall becomes narrower. This outline may reflect a small companion impact uprange or the consequences of a deeper uprange transient cavity.

Figure 48c shows the 59-km-diameter crater Barton with a clearly elongate peak ring, again breached downrange. The uprange crater wall contrasts with the broad downrange wall region. The open peak ring downrange and the broad downrange wall are attributed to successive failure, ricochet, and impact of the impactor during penetration as observed in laboratory experiments. Downrange extensions of the breached peak ring commonly can be traced downrange, as particularly well illustrated in the two-ring basin Bach on Mercury [Schultz and Gault, 1991a]. Again, the crater rim is relatively circular, but the contiguous peak rim is offset uprange.

With increasing crater size, the central peak ring appears offset downrange, rather than uprange (Figure 48c). This reversal from previous examples is attributed to enhanced rim/wall failure uprange as indicated by the structurally controlled step faults on the rim, the concentric zones of failure on the floor below, and the break and displacement of the uprange central peak ring. Oblique impacts in laboratory experiments and in simple craters on the Moon (Messier A and Toricelli) exhibit steep uprange and shallow downrange wall slopes, with the deepest portion of the crater offset uprange.

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**Fig. 47.** Comparison of scaling on different planets based on the hypothesis that central peak dimensions provide a measure of impactor size. From Figure 46, central peak pits represent low-velocity impacts producing a narrow disruption zone beneath the impactor, whereas central peaks indicate crustal response over a broader zone. If central peak pit, central peak, or peak ring diameters $x_0$ are assumed to be proportional to impactor size for a given planet, then using this dimension in the gravity-scaling parameter $r_2$ results in a similar power law exponent of -0.22 but offset. If $2r_i$ is replaced by $2r_i(C_{r0})^{0.5}$, then data for different planets coincide depending on impactor density, velocity, target sound speed, and target density. Assumed impact velocities for producing central peak pits on Mars, Moon, and Mercury correspond to 12, 14, and 32 km/s, respectively, with corresponding values of $c = 4, 3$, and 6 km/s (Figure 47a) and target densities ($\rho_0$) of 3, 2.5, and 3 g/cm$^3$ (impactor density of 2.5 g/cm$^3$). Impact velocities for central peak formation (Figure 47b) are 16 km/s for the Moon and 40 km/s for Mercury (same values of $c$ and $\rho_0$). For peak-ring basins (Figure 47c), impact velocities of 14, 16, and 32 km/s for Mars ($c = 7$ km/s), Moon (5 km/s), and Mercury (7 km/s), respectively, brought the data in line. These results are consistent with expected impact velocities and sound speeds at greater depths.
Fig. 48. Effect of size on the morphology, size, and placement of central peak rings for oblique impacts (<30°). Orientations for each example have been changed such that the impact direction is from the left (large arrow). Figures 48a-48c show the progressive increase in size of the peak ring with respect to crater diameter (bar scale is 25 km). Each example exhibits an uprange offset of the central peak ring consistent with laboratory experiments where the deepest penetration occurs. Additionally, the peak rings in Figures 48b (14.5°N, 350.9°) and 48c (27.4°N, 337.5°) are breached in the downrange direction, similar to craters on the Moon, Mars, and Mercury. Figure 48d (23.5°N, 140.5°), however, appears to exhibit a downrange offset in the central peak ring, but this largely reflects more extensive rim/wall collapse uprange that widens the crater, removes the raised rim, and modifies the peak ring (small arrows inside). The rectilinear pattern of the scarp terraces uprange indicates that failure is controlled by the regional structural grain (not shock effects), as expected if slumping was initiated by an oversteepened uprange wall typical for oblique impacts. As size increases (Figure 48a), uprange collapse becomes still more extensive. The 103-km-diameter crater (52°N, 143.5°) exhibits a well-defined peak ring downrange but modified and displaced ring segments uprange. This modification of the uprange peak ring reflects uprange rim/wall failure that has partially circularized the crater outline. Note that the uprange missing ejecta sector subtends nearly 180°, but linear ejecta flow near the rim subtends a smaller sector (long arrows). The 280-km basin Meade (12°N, 57.5°; C1-15N060) has collapsed to such a degree that the ejecta facies have been partly consumed and the raised rim has been lost. Nevertheless, the slight offset placement of the central ring, surviving ejecta lobes, blast effects, and secondaries all indicate an impact direction from the southeast. The central peak rings referenced to crater diameter for craters smaller than about 90 km should provide data for scaling. Scarp formation and collapse for larger craters destroy these dimensions.
peak rings are offset uprange within the crater floors, reflecting the asymmetric pattern of peak shock pressures demonstrated in laboratory experiments. Second, peak rings typically open downrange, perhaps indicative of successive impactor failure and downrange momentum. Third, as crater size increases, rim/wall failure centers on the uprange portion of the crater rim outline in response to uplift of the deepest portion of the transient cavity created by oblique impacts.

If peak rings provide a measure of impactor size, the transverse diameter of the central peak ring scaled to impactor diameter calculated from equation (6) should be a constant as a function of crater diameter for a given impact angle as shown in Figure 49a. The constant value of this ratio should not be expected if the central peak ring is related to a property of the lithosphere or the size of the crater. If peak ring diameter is proportional to impactor size while crater excavation is controlled by the vertical component of impact velocity, then peak ring diameter should increase relative to crater diameter as shown in Figure 48. Consequently, $D/d_{pr}$ should vary as $(\sin^2 \theta + \alpha^2)^{0.5}$. With the criteria shown in Figure 42, impact angles are assigned as follows: craters with uprange zones of ejecta avoidance are grouped at $\theta = 20^\circ$; craters with obviously asymmetric ejecta but without missing ejecta at $30^\circ$; craters with slightly asymmetric ejecta at $50^\circ$; and craters with relatively symmetric ejecta facies at $70^\circ$ (probability of occurrence is equal to a $20^\circ$ impact angle). Because turbulent-style run-out flows may indicate cometary impactors with higher impact velocities, these craters are further distinguished. Figure 49b reveals that $D/d_{pr}$ increases with $\sin^2 \theta$ as predicted, but the derived slope is slightly greater than expected perhaps due to the assigned impact angles or changes in scaling of crater diameter. Further, it is seen that craters exhibiting turbulent run-out flows generally exhibit higher values of $D/d_{pr}$, an offset consistent with the need for introducing a velocity dependence with $\sin^2 \theta$.

**Crater scaling and shape.** If the relation between impactor size and central relief diameter is given by equation (18), then atmospheric modification of crater scaling will be expressed by an increase in the power law dependence on $\pi_2$ and diameter-depth relations unlike craters on other planets. Figure 50a confirms the first prediction for both peak rings and central peaks. The peak rings exhibit an inflection for diameters greater than $80 \text{ km}$, as expected if enhanced rim/wall failure occurs (Figures 48e and 48f). Scaled crater diameter ($D/2r$) for craters smaller than $80 \text{ km}$ display a power law dependence on impactor radius of $-0.6$, considerably steeper than values for vacuum conditions than either observed (Figure 47) or predicted from equation (15c). Central peak diameter exhibits a very similar dependence. The power law dependence steeper than $-0.48$ may reflect an inappropriate assumption for $\mu$, that is, the coupling parameter exponent. If energy scaling is assumed, $\mu = 0.66$ and $\alpha = 0.75$. With this assumed value, the dependence on $r$ (i.e., $\pi_2$ in Figure 50) becomes $-0.625$, very close to the observed exponent.

If dynamic forces retard crater growth, evidence also may appear in the relation between crater depth and diameter (Figure 45). Without an atmosphere, rim/wall collapse in complex...
thereby paralleling results in the laboratory for loose particulate targets (Figure 44b). The unusually high rim relief from crater profiles [Phillips et al., 1991], however, limits the extent of such collapse. These results can be considered only preliminary since much higher-resolution topographic data are necessary.

In summary, observations are consistent with the hypothesis that central relief diameter is directly proportional to impactor diameter. The existence of numerous relatively small craters (<100 km) with clearly defined central rings helps to establish a unique data base unavailable on other planetary surfaces without introduction of other competing and complicating processes (e.g., onset of multiring formation and uncertain effects due to volatiles). Application of this hypothesis to Venus suggests that craters are significantly smaller (as much as a factor of 2) than if they had formed under turbulent run-out flows

Fig. 49. Size of peak ring scaled to impactor size calculated from equation (6) for craters produced by similar impact angles (Figure 49a) and rim diameter scaled to peak ring diameter for different angles (Figure 49b). From application of Figure 47, peak ring diameter scaled to impactor diameter should be nearly constant over the limited size range. Crater rim diameter scaled to peak ring diameter, however, should increase with increasing impact angles from the horizontal. Impact angle is based on the degree of asymmetry in the ejecta (see text). Moreover, if turbulent run-out flows indicate higher-velocity impacts, crater dimensions should be consistently higher if no correction is made for velocity.

craters enlarges the diameter and reduces the depth (Figure 45a). If crater widening is simply proportioned to the diameter of the transient excavation cavity with relatively little (or constant) shallowing of the depth, then the diameter-depth relation for complex craters eventually parallels simple craters as diameters greatly exceed the onset diameter for rim collapse [Schultz, 1988c]. Mercury appears to exhibit just such a trend at larger diameters. Atmospheric effects restricting lateral crater growth should produce deeper craters at a given diameter unless collapse and uplift occur (Figure 45a). Enhanced collapse of smaller craters on Venus are indicated by the extension above the vacuum line in Figure 50 (as expected in Figure 45b) and by the observed relation between diameter and depth shown in Figure 51. Only representative data are shown in Figure 51 for craters larger than 50 km in diameter in order to clearly resolve just the crater floor in the altimetry footprint. Moreover, craters with large central peaks have been excluded in order to avoid ambiguous averaging of peak relief and crater depth. The diameter-depth relation in Figure 51 is consistent with an atmospheric effect on crater growth resulting in deep transient craters that undergo subsequent enhanced collapse and/or uplift, two-ring basins

Two-ring basins

Fig. 50. Crater scaling on Venus on the basis of (a) central peak and (b) peak ring (cpr) diameters (see Figure 47). Both data sets exhibit a steeper power law dependence consistent with atmospheric restriction of crater growth (see Figure 45b). Two-ring basins (2rb) have been arbitrarily defined as craters larger than 80 km in diameter above which enhanced rim/wall failure occurs. Crater enlargement should result in data above the extrapolated trend from smaller craters, as observed.
vacuum conditions. Such a conclusion would further reconcile the factor of 2 disparity in the upper limit for impactor diameter derived from the largest atmospheric blast haloes relative to the lower limit calculated from scaling relations for the smallest single craters. Reduction in cratering efficiency also reduces the total projectile mass represented by the long run-out flows. And the inferred reduction in efficiency helps to understand the greater visibility of early time processes expressed by the central peak complexes and effects of downrange impactor ricochet. An obvious consequence of such a conclusion is that surface age based on crater statistics may be significantly underestimated not only due to atmospheric shielding reducing the number of craters smaller than 30 km in diameter [Phillips et al., 1991] but also due to a reduction in crater diameter.

5. CONCLUDING REMARKS

The dense atmosphere of Venus plays a significant role in modifying the sequence and style of ejecta emplacement around impact craters as summarized in Table 6 and Figure 52. Comparisons between the surface record revealed by Magellan and processes inferred from laboratory experiments indicate that the atmosphere not only shields the surface from small-body collisions but also preserves important signatures of early time processes lost on other planets. Energy transferred from impactor to the atmosphere occurs prior to impact or indirectly afterward through deceleration of ejecta and impact-generated vapor. Direct coupling with the atmosphere is expressed as crater-less radar-bright scour zones created by catastrophic impactor disruption and collision from the residual wake. This process can be viewed as atmospheric cratering. First-order estimates of the maximum impactor size undergoing such failure are about 3.4 km in diameter. Smaller, stronger (denser) objects may survive entry to the surface within a muck column. Larger, weaker objects may survive to a level in the atmosphere where impactor density approaches the compressed atmospheric density in its leading air cap. For cometary objects this should occur at altitudes between 10 and 20 km.

As larger impactors survive entry, energy directly coupled to the atmosphere decreases as energy is first transferred to the target, then to the atmosphere. This early time indirect energy transfer reflects deceleration of retained kinetic energy in the impactor and containment of internal energy (expanding vapor cloud). For oblique impacts, early time coupling with the atmosphere occurs well before crater excavation and is spatially separated downrange. Signatures of indirect energy transfer include downrange offsets of the following features: radar-bright haloes, rim depressions, standoff and turbulent ejecta emplacement, asymmetric radar-dark parabolas, and reworking of ejecta during atmospheric recovery.

Containment and deceleration of impactor, vapor, and melt result in highly fluid deposits emplaced well before arrival of ejecta from crater excavation. These early time run-out flows develop from density flows collapsing within the lower-density disturbed atmosphere and depend on impact trajectory (direction and angle). Impact direction controls flow to about a crater radius from the rim before following local slopes. Run-out flows exhibit distinctive styles that can be classified as turbidity flows resulting in transparent deposits or laminar lavalike flows. It is proposed that these two distinct styles largely reflect properties of the impactor and that radar properties (emissivities) may be used to characterize impactor properties.

Fig. 51. Relation between crater depth and diameter based on profiles derived from altimetry data. Craters were selected in order to minimize possible ambiguities from central peaks. Results are consistent with atmospheric effects (Figure 45a), but more detailed studies are required.

Fig. 52. Proposed scenario for sequence and processes associated with ejecta emplacement and crater formation on Venus. (a) Early time sequence depicts initial transfer of impactor kinetic energy to target and atmosphere (Figure 1). (b) Late time sequence shows the complex atmospheric response to the strong shocks created at early time (Figure 25a). Differences in recovery times between the atmosphere and target results in surface interactions not found on the Moon and Mercury. See Table 6 for summary of observations and interpretations illustrated by cited figures.
**TABLE 6. EJECTA EMPLACEMENT PROCESSES in Approximate Sequence**

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types further. Turbidity flows are suggested to indicate volatile-rich impactors (25% of the crater population) that cannot recondense under the high temperatures and pressures, whereas laminar emplacement styles indicate silicate or iron-rich impactors (58%). Laminar flows with distinctive radar characteristics may indicate Fe/Ni impactor compositions. Turbidity flows may indicate very high-velocity and/or volatile-rich silicate impactors (17%). Estimates of run-out flow mass suggest impactor contamination ranging from 10% to 80% (depending on assumptions) that increases with decreasing impact angle. Very late stage turbidity flows may achieve enormous distances due to turbulence from latent heat release as the vapor condenses to form melts.

Indirect energy transfer at late times occurs from deceleration of ejecta and dynamic response to the outward moving ejecta wall. Although ejecta are clearly excavated ballistically, they are emplaced in a nonballistic ground-hugging flow as indicated by deflection around low-relief hills, slope control of their course, and relative timing of emplacement. Intense turbulence created by the pressure differential inside and outside the curtain scours the near-rim ejecta and creates a coarse lag surface that retains a fresh-appearing signature, even for very old craters. Separation of the boundary layer (flow separation) behind this advancing ejecta cloud results in further run-out of entrained finer fractions producing radar-dark lobes extending beyond the inner radar-bright deposits. Direct evidence for atmospheric modification of ejecta emplacement is recorded in redirected ejecta flows, drawn downrange by recovery winds. Late stage fallout from recondensed vapor lofted in the early time fireball (Venus analog of terrestrial tektites) contributes to the distinctive parabolic pattern but expression depends on impact direction, angle, topography, and crater size.

The observed modification of ejecta emplacement by the atmosphere also may be accompanied by decreased cratering efficiency. Correlation between placement, morphology, and dimensions of central peaks and peak rings as a function of impact angle suggests that they provide a measure of impactor size, thereby allowing first-order tests of scaling relations. Correlation of Z with other planetesimals suggests that crater scaling relations on Venus are controlled by atmospheric effects, rather than gravity. If these conclusions are correct, then the depths and diameters of complex craters (rim/wall collapse) should resemble simple craters unless more extensive rim/wall failure occurs. The inferred reduction in cratering efficiency is repeatedly encountered in other estimates of impactor size from atmospheric effects. Hence the atmosphere may affect surface chronologies not only by filtering out small bodies but also by reducing crater diameter.

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