Ejecta entrainment by impact-generated ring vortices: Theory and experiments

O. S. Barnouin-Jha and P. H. Schultz

Department of Geological Sciences, Brown University, Providence, Rhode Island

Abstract. Laboratory experiments indicate that an advancing ejecta curtain displaces the atmosphere and creates strong winds that entrain large amounts of fine-grained ejecta. A theoretical model describing the interaction between an atmosphere and the outward moving ejecta curtain allows one to estimate the magnitude and velocity of the winds in the induced ring vortex in order to establish the importance of such winds at planetary scales. Model estimates for the initial magnitude of the flow within the basal vortex match experimental results within observational uncertainty and reveal that the flow in the ring vortex is turbulent. Successful comparisons of the vortex generation model with experiments allow preliminary applications to be made at much broader scales. Curtain generated winds by a 30-km-diameter crater should entrain ejecta particle diameters smaller than 5 mm on Mars, 30 cm on Earth, and 8 m on Venus.

Introduction

Ejecta trajectories from an impact generate a curtain, forming an inverted hollow cone or frustum that expands outward [Gault et al., 1968; Oberbeck, 1975]. In an atmosphere, the lower portion of the ejecta curtain acts as a barrier that forces atmosphere around it, causing flow separation at its top edge [Schultz and Gault, 1979, 1982; Schultz, 1992a] in a manner similar to when flow impinges upon a knife's edge [Prandtl and Tietjens, 1934]. A ring vortex forms behind this advancing curtain. Airflow impinging on the curtain and within the vortex decelerates and entrains sufficiently fine grained ejecta (Figure 1). As the flow decays, winds in the vortex may initially scour ejecta and target surfaces, with the coarse grained ejecta deposited in contiguous ramparts, and finer fractions in flow lobes. Such features are strikingly similar to nonballistically emplaced ejecta deposits on Mars, Earth, and Venus. Evidence consistent with atmospheric effects on ejecta emplacement includes (1) absence of secondaries around craters with fluidized ejecta on Mars [Schultz and Singer, 1982]; (2) two stages of ejecta emplacement where the outer lobe of multiple impact craters on Mars and Venus override the inner ejecta lobes [Schultz and Gault, 1979; Schultz, 1992b]; (3) order of magnitude estimates of the wind intensity created by the curtain exceed present-day wind strengths known to transport eolian material [Schultz, 1992a]; (4) nonballistic emplacement of ejecta indicated by deflections around obstacles [Schultz, 1992b]; and (5) consistency of first-order run-out distances with crater size and with regional lithology [Schultz, 1992a].

Other proposed mechanisms describe the nonballistic emplacement of ejecta facies on planets. One mechanism has been attributed to the presence of water or volatiles which would reduce the viscosity in initially ballistically emplaced ejecta and result in flows similar to mud-slide [Carr et al., 1977; Mouginis-Mark, 1979; Gault and Greeley, 1978; Greeley et al., 1980; Horner and Greeley, 1982; Mutch and Woronov, 1982; Ivanov et al., 1994]. Schultz [1992a] suggested that such water-saturated ejecta most likely characterizes the inner facies in certain highly fluidized ejecta styles. Alternatively, volatiles vaporized at impact might entrain some ejecta into a debris cloud that would flow as a density current and deposit ejecta [Carr et al., 1977; Wohletz and Sheridan, 1983].

Nonballistic ejecta features also could result from secondary cratering. Secondary impacts might create a flow-like debris surge of primary and secondary ejecta [Hörz et al., 1977, 1983; Hörz, 1982]. An atmosphere entrained in the falling ejecta could enhance turbulence created by the ballistic process generating flow-like features [Hörz, 1982; Schaber et al., 1992], although the specific mechanics of this process were not discussed. Volatiles released and entrained during secondary cratering could enhance run-out during ejecta emplacement on Mars [Schultz, 1992a].

Because an atmosphere also causes the ejecta curtain to decelerate and steepen to near vertical, gravity could cause ejecta small enough within the curtain to collapse [Schultz and Gault, 1979]. Ejecta would then flow downward and outward, sliding along the surface as a sturzstrom as described by Hsü [1975] for avalanches to produce lobate structures [Schultz and Gault, 1979, 1982; Herrick and Phillips, 1994]. Other than initially decelerating the ejecta, the collapsing ejecta model of Herrick and Phillips [1994], however, ignores the action of the ejecta curtain on the atmosphere.

Laboratory-scale experiments and simplified calculations suggest that curtain-driven vortex winds may strongly affect ejecta entrainment and deposition during planetary cratering [Schultz, 1992a, b]. However, previous calculations of the strength of these winds were based simply upon the advancing velocity of the ejecta curtain [Schultz, 1992a]. The present study develops a fluid dynamical model for the generation and initial decay of these curtain-driven winds, thereby addressing quantitatively the physical processes responsible for the winds formation and importance at broad scales. The winds calculated by the model are the result of the ejecta curtain mechanically displacing the surrounding atmosphere at late stages in the impact process to produce a ring vortex. Such a ring vortex is not the result of shock and thermal effects that occur early in the cratering process, well before late-stage...
near-rim emplacement of ejecta [e.g. Artem'ev et al., 1994]. Experiments at the NASA Ames Vertical Gun Range (AVGR) test the theoretical model and indicate that it satisfactorily estimates the initial circulation generated in the lowest vortex created behind the curtain. Such comparisons allow extrapolations to planetary scales for a variety of atmospheric and impact conditions. Preliminary results indicate that the winds generated by the curtain on planets with atmospheres are sufficient to entrain significant ejecta sizes on Mars, Earth, and Venus and should significantly affect the deposition process. We do not address mechanisms for final ejecta deposition in this study; rather we focus on the mechanics by which an ejecta curtain generates strong winds, thereby entraining and carrying ejecta prior to its deposition.

Theory

In order to determine the variables which control the strength and behavior of the winds created by an advancing curtain, we evaluate the physical processes primarily controlling the complex flow created by the curtain. An ejecta curtain contains sufficient debris to create an impermeable barrier to the surrounding atmosphere. Consequently, the ejecta curtain can be viewed as an impermeable solid plate. We first focus on the variables controlling the ring vortex shed behind this advancing barrier, which laboratory experiments indicate are responsible for the entrainment and deposition of fine grained ejecta. These variables then permit computing the start-up circulation and core radius of the ring vortex first created by the advancing impermeable ejecta curtain. They also allow modeling the decay of the flow in the vortex, the growth of its core radius, and the outward motion of the core of the ring vortex position after the ejecta curtain becomes permeable.

As the curtain moves outward, flow separation occurs at the upper end of its lower thicker, denser portion. The decelerating ejecta curtain creates two ring vortices with opposing flow directions [Schultz and Gault, 1982; Schultz, 1992a] in order to conserve angular momentum in the fluid near the tip of the impermeable ejecta curtain. Ring vortices also develop near the tip of a decelerating knife's edge [Prandtl and Tietjens, 1934], and this similar response prompts viewing the ejecta curtain as an impermeable solid-like barrier. If the curtain moves from left to right, the upper vortex possesses a clockwise flow while the lower vortex possesses a counter-clockwise flow (Figure 2; see Table 1 for variables used in the theoretical models). Laboratory observations indicate that the lower or basal vortex controls the emplacement of fine grained ejecta, while the upper vortex dissipates rapidly [Schultz, 1992a, b]. Consequently, this study focuses only on the dynamics of the lower vortex.

Shear stresses acting at the inner surface of the ejecta curtain due to the upward motion of individual ejecta in the curtain probably do not affect the formation of the lower vortex. To demonstrate this, a solid plate analogy for the ejecta curtain indicates that the shear stress \( \tau \) acting on the lower vortex by ejecta particle motion in the curtain is given by [Rosenhead, 1963; White, 1986]

\[
\tau = 0.33206 \rho u^2 (ux/v)^{-1/2} \\
\tau = 0.0135 pu^2 (uxv)^{1/7}
\]

for laminar and turbulent flow respectively; \( \rho \) is atmospheric density; \( v \) is the kinematic viscosity; \( x \) is the distance from the top edge of the curtain; and velocity

\[
u = \lvert v_f - u_p \rvert
\]

The magnitude of the atmospheric flow velocity \( v_f \) due to flow...
separation in the basal vortex equals the velocity of the advancing curtain \( U \) at the back surface of the curtain to within a factor of 2. The component of the velocity \( u_p \) of the ejecta particles in the lower portion of the curtain travels parallel to the curtain's inner surface with a similar magnitude \( U \). Consequently, equation (2) indicates that \( u \to 0 \) for the lower vortex because individual ejecta in the curtain move parallel to the flow in the vortex, thereby maintaining \( x \) small. Actually, the flow velocity in the lower vortex could be increased if \( u_p \) is slightly greater than \( v_f \), although this effect should be small.

A flow separation model therefore should allow a reasonable estimate for the circulation or strength of the flow generated in the lower ring vortex, since shear drag is minimal. Laboratory observations also indicate that the region of flow separation at the top of the curtain is small compared to the impermeable portion of the curtain when the vortex is first created. For such conditions, existing theory allows estimating the circulation created by a vertical plate advancing at a constant velocity from rest into an inviscid and incompressible fluid [Anton, 1939; Wedemeyer, 1961]. The solution for the flow field that allows calculating this circulation was determined by applying Kaden's [1931] assumption that the vortex sheet created by flow separation is a spiral satisfying a law of similitude. The solution maintains finite flow at the top of the edge of the plate (i.e. Kutta-Joukowski condition) while matching the velocity field of a line vortex located at the edge of the plate with that ahead of the plate. Experiments show that such theoretical solutions adequately reproduce the growth of a vortex sheet formed at the edge of a vertical plate [Rott, 1956; Wedemeyer, 1961].

To determine the circulation for the start-up vortex sheet of the ejecta curtain, we consider the curtain traveling at an angle of about 45° with respect to a horizontal target surface [Gault et al., 1968]. Solutions for the circulation and vortex growth of the flow behind a 90° wedge or triangular block provide an analogy for the behavior of the flow due to separation on the back side of an ejecta curtain. Using Kaden's [1931] and Anton's [1939] approach, Rott [1956] found a first order asymptotic solution for such a wedge which differed significantly from experimental results. Possibly the use of the Kutta-Joukowski condition for such a large wedge angle no longer applies because the upper edge of the wedge is not as sharp as the edge of a plate [Rott, 1956]. Furthermore, experimental and numerical evidence indicates that viscosity plays an important role in forming a second small, counterrotating vortex near the point of flow separation which is not accounted for in the inviscid models [Rott, 1956; Pullin, 1978]. Fortunately, both of these issues are not significant when considering an advancing ejecta curtain. First, the back surface of the curtain travels at velocities comparable to the velocities generated by flow separation in the fluid behind the curtain, thereby eliminating any viscous stresses. Second, the Kutta-Joukowski condition must apply because the flow impinging upon the curtain is observed in experiments to bend sharply around the impermeable portion of curtain, thereby resembling the edge of a plate rather than a wedge [Schultz and Gault, 1982; Schultz, 1992a].

Even though the solutions of flow around a wedge do not apply strictly to the problem of the ejecta curtain, laboratory experiments reveal the theoretically expected flow behavior. For example, a robust feature of numerical solutions that maintain both inviscid flow and the Kutta-Joukowski condition is a spiral vortex that is not subject to any viscous stresses. Experimentally, a spiral vortex near the point of flow separation which is not accounted for in the inviscid models [Rott, 1956; Pullin, 1978]. Fortunately, both of these issues are not significant when considering an advancing ejecta curtain. First, the back surface of the curtain travels at velocities comparable to the velocities generated by flow separation in the fluid behind the curtain, thereby eliminating any viscous stresses. Second, the Kutta-Joukowski condition must apply because the flow impinging upon the curtain is observed in experiments to bend sharply around the impermeable portion of curtain, thereby resembling the edge of a plate rather than a wedge [Schultz and Gault, 1982; Schultz, 1992a].

To estimate the circulation or flow strength of the vortex sheet created behind the advancing ejecta curtain, we adopt the same assumptions as for the solution of flow past a vertical plate [Anton, 1939; Wedemeyer, 1961] but include the effect of the curtain slant. We assume that the relative conditions necessary to maintain the Kutta-Joukowski condition for a vertical plate vary geometrically with changes in curtain slant as prescribed by the spiral determined by Kaden [1931], which satisfies the laws of similitude. Using the result of Wedemeyer [1961] for a vertical plate as a reference, the circulation \( \Gamma \) generated in the lower vortex sheet is given by

\[
\Gamma = 2\pi \left( \frac{1}{0.13 + \theta} \right)^{1/3} \frac{1}{L} \frac{UL}{V} \left( \frac{\rho}{\rho_0} \right)^{1/3}
\]

(3)

where \( \theta \) is the curtain angle with respect to the surface, \( L \) is the curtain length, and \( U \) is the curtain velocity. Technically, \( t_p \) is the time from when the impermeable portion of the curtain en-
ters the ambient atmosphere to when the curtain becomes permeable. In this study, we assume that for both small and large scale impacts, \( t_i \) equals the time from impact to when the curtain becomes permeable. This solution for the circulation incorporates the first-order physics of flow separation of an atmosphere by the advancing ejecta curtain.

Both theory and observations indicate that the vortex is elliptical in shape. Nevertheless, the modified formulation of Wedemeyer [1961] provides an adequate description of the average radius \( r_c \) of the vortex core (refer to Figure 2):

\[
r_c = \left( \frac{1}{0.13 \pi + \theta} \right)^{2/9} \left( \frac{L}{2.0 \pi + \theta} \right)^{2/3} \left( \frac{U_i}{L} \right)^{2/3}
\]

This radius defines the position where the flow in the vortex achieves a maximum. Flow velocity outside this core decays as \( 1/r \) where \( r \) is the radius from the center of the vortex core, and decreases linearly to zero at the center of the vortex core. The core of the ring vortex is small compared to the region influenced by the vortex flow.

Equations (3) and (4) indicate that the circulation and the vortex core radius are primarily dependent upon the velocity of the ejecta curtain and then to a lesser extent upon the length of the curtain. Thus variations in the impermeable length of the curtain, growing and shrinking while it advances into the surrounding atmosphere, should not significantly affect the magnitude of the flow and size of the vortex core. However, variations in the velocity of the curtain should be very significant.

Once the ejecta curtain becomes permeable, we assume the magnitude of the flow in the vortex is no longer controlled by the motion of the ejecta curtain. The flow in the vortex can be controlled by (1) the flow in the vortex affecting itself, (2) shear stresses acting on the ring vortex at the target surface, and (3) atmospheric viscosity. The flow within the vortex core affects the position in space of the core itself. Considering the counterclockwise streamlines of the vortex core on the right side of the impact-induced ring vortex, one imagines that these streamlines extend to infinity. These streamlines push the core at the left side of the ring vortex downward. Similarly, the streamlines on the left side of the ring vortex push the right side of the ring vortex downwards. Occurring simultaneously, such interactions move the entire ring vortex down toward the target surface (see Figure 2). Once at the surface, these interactions keep the ring vortex at the target surface at least initially [Lamb, 1932; Magarvey and MacLatchy, 1979; Shariff and Leonard, 1992].

Experiments and numerical calculations of smoke rings crashing into a rigid boundary show that the center of the core of the ring vortex will remain at a height approximately equal to the radius of the vortex core before they disintegrate [Magarvey and MacLatchy, 1979; Shariff and Leonard, 1992].

The streamlines not only move the entire ring vortex, they also may strain and alter the flow within the vortex core. The significance of this effect depends on the velocity of the flow from one side of the vortex acting on the other. In the case of an impact at late time, however, the radius \( r_c \) of the vortex core is small compared to \( R \), the toroidal radius of the vortex ring. Since the velocity in a vortex core decreases as \( \Gamma/2\pi r \) where \( r \) is the distance from the center of the vortex core, the flow from one side of the ring vortex has little effect upon the flow on the other side, where \( r - 2R \gg r_c \). Furthermore, experiments indicate that the core of the basal ring vortex moves outwards following the ballistic ejecta curtain [Schultz and Gault, 1982]. This extends the toroid radius \( R \) and reduces the effect of the flow within the vortex core. Because \( R >> r_c \), we can assume that the vortex behaves in a linear and planar fashion. Hence the flow in the impact-induced ring vortex will be modeled to first order by a planar line vortex with some slight modifications (discussed below).

Because the flow in the core pushes the entire ring vortex down toward the surface, surface shear stresses eventually should reduce the flow velocity in the vortex core. Such shear also should enhance any instabilities that may have existed in the core when the vortex was first created, thereby eventually causing the ring vortex structure to breakdown [Magarvey and MacLatchy, 1979]. When the vortex first reaches the target surface, however, surface shear effects will be minimized because the shear stresses are confined to a small boundary layer at the surface. For this reason and because this study focuses on evaluating the initial strength and behavior of the winds created by the advancing curtain (rather than on its decay), surface shear stresses are not considered.

Atmospheric viscosity plays a key role in vortex evolution (growth and velocity) after it separates from the curtain and causes the flow in the vortex to decay as a function of time. Since a planar geometry can be assumed, an Oseen or Lamb line vortex model is used to approximate the effect of atmospheric viscosity on the impact-induced vortex. Such a model successfully describes the flow in thin smoke rings \( r << R \) [Sallet and Widmayer, 1974]. When the flow in the vortex is laminar, the axial velocity in the Oseen line vortex is given by

\[
V_\theta = \frac{\Gamma}{2 \pi r} \left( 1 - e^{-\frac{r^2}{4V(t-t_i)}} \right)
\]

where \( t \) is the time since impact; \( t_i \) is the time for the Oseen vortex to reach the core radius \( r_c \) when the vortex detaches from the advancing curtain; and \( V \) is the kinematic viscosity. The radius of the vortex \( r_{max} \), where the velocity in the vortex core reaches a maximum is given by

\[
r_{max} = 2.245 \sqrt{V(t-t_i)}
\]

Ring vortices created by an accelerating piston are found to be turbulent [Sallet and Widmayer, 1974]. Since the motion of an ejecta curtain resembles a decelerating piston, we consider the possibility of turbulent flow: we replace the kinematic viscosity \( V \) with an effective kinematic viscosity \( V_{eff} \) that enhances the rate of viscous decay as a function of the Reynolds number in the flow of the ring vortex. Here we choose the model proposed by Owen [1970] where

\[
V_{eff} = 0.6108 \left( \frac{\Gamma}{\nu} \right)^{1/2}
\]

and \( \Gamma/V \) is the Reynolds number for flow in the vortex. This model is simplified where steep stress gradients separate an inner annulus that is strain-free from the outer irrotational flow. Although Owen's [1970] detailed assumptions may be heuristic, his model proves to agree adequately with
experiments over a wide range of Reynolds numbers including for vortices shed off commercial jet airfoils [Bradshaw, 1973]. This model tends to slightly overestimate vortex decay at laboratory scales while accurately estimating decay at larger scales [Owen, 1970].

Unlike the experiments of Sallet and Widnayer [1974], the curtain-generated basal ring vortex expands outward. The Oseen line vortex model therefore must be modified to maintain energy and angular momentum constant for the ring vortex as the vortex expands in three dimensional space. In order to conserve energy, the flow velocity in the vortex core must decrease as $1/xR$ where $R$ is the vortex toroid radius (see Figure 2 and the appendix). The circulation $\Gamma$ in (5), (6), and (7) must then be replaced by $\Gamma(R_0/R)^{1/2}$ where $R_0$ equals $R$ when the curtain becomes permeable. In order to conserve angular momentum, the radius of the vortex $r$ must decrease as $(1/R)^{2/3}$ (see appendix). This is equivalent to replacing the time $(t-t_i)$ in equations (5), (6) and (7) by $(t-t_i)(R_0/R)^{1/2}$. In a qualitative sense, such an approach models vortex stretching, since replacing $(t-t_i)$ by $(t-t_i)(R_0/R)^{1/2}$ increases the velocity in the vortex core while reducing its radius. The new axial velocity in the vortex will be

$$V_\theta = \frac{\Gamma}{2\pi} \left( \frac{R_0}{R} \right)^{1/2} \left( 1 - e^{r^2} \right)$$

Again, $v$ and $v_{eff}$ can be interchanged to explore the effects of turbulence.

The outward motion of the vortex core away from the impact center can be estimated using the method of images [e.g., White, 1986]. Since the ring vortex is not strongly affected by the target surface, inviscid flow theory allows us to place an image of the ring vortex below the surface, thereby replacing it with a plane-surface streamline. As the flow in the ring vortex tends to move down, the image of the ring vortex in the target surface forces the vortex to open outwards (see Figure 2). This outward velocity of the vortex is given by

$$V = \frac{\Gamma}{4\pi y} \left( 1 - e^{-y^2} \right)$$

where $y$ is the height from the vortex core center with respect to the target surface when the flow in the vortex is considered planar and unaffected by the lateral expansion of the ring vortex. When we conserve energy and angular momentum for an expanding ring vortex, the outward velocity of the vortex is given by

$$V = \frac{\Gamma}{4\pi y} \left( 1 - e^{-y^2} \right)$$

Here, too, $v$ and $v_{eff}$ can be interchanged to explore the effects of turbulence.

**Table 2. Empirical Data**

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<td>0.376</td>
<td>2.17</td>
<td>0.67</td>
<td>air</td>
<td>24 sand</td>
</tr>
<tr>
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<td>0.635</td>
<td>0.376</td>
<td>2.17</td>
<td>0.75</td>
<td>air</td>
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<td>0.376</td>
<td>2.19</td>
<td>0.75</td>
<td>air</td>
<td>24 sand</td>
</tr>
</tbody>
</table>
Table 3. Ejecta Properties

<table>
<thead>
<tr>
<th>Ejecta Type</th>
<th>Grain Size, ( \mu m )</th>
<th>Density, kg/m(^3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>24 sand</td>
<td>457</td>
<td>1700</td>
</tr>
<tr>
<td>Microspheres</td>
<td>100</td>
<td>500</td>
</tr>
</tbody>
</table>

Experiments

The above theory can be tested experimentally by first measuring the parameters necessary to compute both the circulation and the radius of the vortex sheet created by an advancing ejecta curtain. Once the circulation \( \Gamma \) and the radius of the core of the start-up ring vortex are estimated, computations can be compared with measurements of the vortex size during formation and decay, as well as with the position of the vortex core as a function of time. Because the theory for the flow velocity within the vortex and the position of the vortex core as a function of time applies to a single phase fluid, our experiments are designed to minimize ejecta entrainment.

Quarter-space experiments (Figure 3; Table 2) at the NASA AVGR allow one to measure the variables necessary to compute both the circulation and the radius of the ring vortex just before the curtain becomes permeable, as well as the radius and position of the ring vortex thereafter. A coarse sand target (24 sand in Table 3) creates a sufficiently impermeable ejecta curtain to induce flow separation and a ring vortex. The magnitude of the flow, however, is insufficient to entrain the sand [Schultz, 1992a]. In order to visualize the flow without significantly altering the kinematic viscosity and density of the flow, small microspheres (Table 3) are placed on the target. A high-speed video camera (500 and 1000 f/s) permits measuring all the time-evolving variables necessary for the comparison between theory and experiment: the length \( L \) of the impermeable ejecta curtain; the position of the curtain; the radius \( r_c \) (or \( r_{max} \) after curtain becomes permeable) of the core of the ring vortex; and the height and outward motion of the core of the ring vortex. Careful analysis of the video also allows one to determine the approximate time \( t_p \) when the curtain becomes permeable and the time of crater formation (unaffected

![Figure 4](image_url)

Figure 4. Measured (solid squares) and calculated (open diamonds) radius of initial (start-up) vortex core as a function of time (\( t \)) normalized to the time of crater formation (\( T \)) for different experiments. The close match between theory and observations indicates that the start-up model of equation (3) estimates well the circulation in the vortex. The shaded area shows the experimental uncertainties due the measurements of \( L \), \( U \) and \( t_p \) used to the calculate theoretical vortex radius. Because the vortex core possesses an elliptical shape, the error bars indicate the size range of its semimajor and semiminor axes.
Figure 5. Measured (solid squares) and least squares fit (curves) of vertical height (y) of the core of the ring vortex scaled to the crater radius (Rc) as a function of dimensionless time (time, t normalized to the time of crater formation, T). The turbulent models depart from the least squares fit of the observed data because the theoretical estimate of the diameter of these turbulent ring vortices exceeds their observed height. The solid curve excludes any effects due to the lateral growth of the ring vortex (ideal turbulent model, or ITM). The dashed curve considers only the conservation of energy (energy conservation turbulent model, or ETM). The dotted curve conserves both energy and angular momentum while the ring vortex expands horizontally (realistic turbulent model, or RTM).

by the presence of the atmosphere for the target used). By fitting a power law to the position of the curtain as a function of time (basically a Z-model [Maxwell, 1977]) we evaluate the velocity U of the advancing curtain in time.

With measurements of L, U and t_p, equation (4) allows one to estimate theoretically the radius r_c of the core of the ring vortex, which then can be compared directly to measured values of r_c (Figure 4). In addition, measurements of the vortex height allow computing the horizontal position of the core of the ring vortex as a function of time. When the vortex radius r_max exceeds this height, it is maintained at a height equal to r_max, avoiding the unreasonable situation where the vortex core theoretically proceeds under the target surface (Figure 5). Such an assumption is consistent with numerical calculations and laboratory experiments [Magarvey and MacLatchy, 1979, Shariff and Leonard, 1992]. The theoretical results are compared with the outward measured motion and radius of the vortex obtained from the video after the curtain becomes permeable (Figures 6, 7 and 8). For all calculations after the curtain becomes permeable, we consider both turbulent and laminar flow in the vortex, but neglect the effect of surface shear stresses when the vortex first reaches the surface. The above variables also allow one to compute the expected vortex flow velocity at the target surface. In order to test the theory further, these models’ flow velocities are compared to the velocity of small Styrofoam balls placed on the target which the vortex pushes outward after the passage of the curtain (Figure 9).

Uncertainties in the theoretically derived values are due to uncertainties in the measured values of L, U and t_p (see Figures 7-9). Most of the uncertainty arises from measures of the curtain length and the time when the curtain becomes impermeable. To determine the length of the curtain, we establish as accurately as possible the position where the flow rushes over the top of the curtain. This position is indicated by the fine microspheres in the ejecta curtain which are stripped away by the flow traversing through the top permeable part of the ejecta curtain. Repeated measurements suggest that this length can vary by about 1 cm.

The ejecta curtain does not become permeable suddenly, but over a small time period as the slow ejecta in the curtain begin to deposit ballistically and the fast ejecta separate from each
other. At laboratory scales, observations suggest this time period is small. We therefore assume that the change from an impermeable to permeable curtain occurs instantaneously, and we define \( t_p \) as the time when this change begins. Repeated measurements show that this time can vary by 0.002 to 0.01 s. The time of crater formation at laboratory scales approximates 0.1 s.

Uncertainties also arise when measuring the vortex core radius. To determine the size of the vortex core, we assume that the distance from the vortex center to the region where most of the microspheres are entrained equals the radius of the core of the vortex. This should be a good assumption for the radius of the vortex core, since the velocity in the vortex is a maximum at this point.

The Plexiglas sheet used in quarter-space experiments cuts the crater and ejecta curtain in two but interferes with the advancing motion of the portion of the ejecta curtain only where it contacts. As a result, we focus on the curtain and the flow a few centimeters behind the sheet. This is achieved by placing the microsphere tracers a few centimeters away from the Plexiglas. Observations demonstrate that the presence of the Plexiglas does not significantly affect the flow at this distance, consistent with boundary layer theory.

Additional measurement uncertainty may arise when we attempt to distinguish between flows that occur a few centimeters from the Plexiglas and those that occur farther behind the Plexiglas. These uncertainties arise because the flows separating from the top edge of the half ejecta plume possess a three-
dimensional character. As a solution, the vortex furthest from the impact point traveling parallel to the plane of the Plexiglas is measured.

Results

In order to determine how well theory predicts the observed behavior of the ring vortex during its creation and initial decay, we compare observation with theoretical estimates of (a) vortex initiation and growth, (b) vortex motion, and (c) vortex wind velocities.

Vortex evolution. Within experimental error, the theoretically estimated start-up radius and the observed radius of the core of the ring vortex are very nearly identical (Figure 4). Once the curtain becomes permeable, the observed radius of the core of the vortex grows (Figure 6). Indeed, it grows more rapidly than expected theoretically if the flow in the vortex is laminar ("laminar model" or LM) but more slowly than expected if the flow in the vortex is turbulent ("turbulent model" or TM). The turbulent model that conserves both momentum and kinetic energy ("realistic turbulent model" or RTM) best fits the observed growth of the core of the vortex ring.

Motion of core of vortex. The observed motion of the core of the ring vortex exhibits four stages that are matched to differing degrees by the theory. During stage I, the curtain is impermeable. The vortex core closely follows behind the curtain accelerating rapidly to position S of Figures 7 and 8. Position S (for Start) indicates approximately where the ejecta curtain becomes permeable. In stage II, the vortex toroid radius increases at a constant velocity along a straight line stretching from S to a time 2-3 times longer than the time of crater formation (T). All the theoretical models considered in this study adequately match the position of the vortex core center during this stage and each model is indistinguishable from the next. Stage III begins at t/T ~ 3 when the outward motion of the core of the ring vortex accelerates, eventually
reaching a greater but constant velocity. All the theoretical models predict qualitatively this observed increase in the expansion velocity of the toroid radius of the ring vortex as well, but differ in the exact position of the core of the ring vortex during this stage. The estimates from turbulent models (TMs) place the vortex core closer to the impact center than observed, while the laminar models (LMs) place it farther than observed.

Some experiments appear to exhibit a fourth stage in the motion of the vortex that occurs after \( t/T \approx 4 \) (see Figures 8 b, c and maybe d). In this stage, the observed expansion velocity of the toroid radius of the ring vortex decreases. Only the turbulent models qualitatively predict such a motion.

Wind Velocities. The Styrofoam balls placed on the target surface act as tracers of the flow velocity in the ring vortex at the target surface. Their velocity decreases as a function of time consistent with the absolute flow velocities predicted by the turbulent flow models (Figure 9). Small scale variations in the velocity of the tracers reflect other secondary processes that affect the advance of the particles as they move along the target surface. The LMs predict slightly greater absolute velocities and an overall increase in these velocities in time. The ideal turbulent model where neither energy nor angular momentum is conserved (ITM) and the RTM best fit the observations.

Discussion

The results indicate that the theory generally accommodates the observations. Consequently, the theory is believed to take into account the primary physical mechanism controlling the behavior of the ring vortex at the time of flow separation and immediately thereafter. Furthermore, results show that the flow in the ring vortex is most likely turbulent. The difference between laminar or turbulent flow in the ring vortex cannot be readily determined by simply evaluating the Reynolds number of its flow because turbulence has several origins in a vortex ring [e.g. Sallet and Widnayer, 1974]. Small discrepancies...
Figure 9. Observed and theoretical wind velocities created by the ring vortex as a function of dimensionless time (as in Figure 5). Top two graphs illustrate TM results; the bottom two graphs illustrate LM results (see Figure 6). The solid, dashed and dotted curves are defined in Figure 6. Shaded regions show the range in model estimates due to observed range of $L$, $U$, and $t_{ed}$; their shading scheme is defined in Figure 8. The RTM or RLM range overprints the ETM or ELM range and both overprint the ITM or ILM range. Observed wind velocities are based on the motion of entrained low-density Styrofoam balls placed on the surface. Small-scale variations in the velocity reflect second-order perturbations affecting the balls’ advance along the target surface. Error bars reflect range of velocities obtained for Styrofoam balls from measurements.

nevertheless arise between theory and observations. Such discrepancies can be largely attributed to additional physical phenomena of secondary importance affecting the ring vortex.

Comparisons between observation and theory.

The observed and estimated radii of the start-up vortex present the best match between observation and theory. Both radii are essentially identical within experimental uncertainty and demonstrate that flow separation is most likely the primary physical mechanism controlling the creation of the ring vortex when the curtain remains impermeable. Moreover, shear stresses acting at the inner surface of the ejecta curtain do not seem to play an important role at the early stages of vortex generation (before $S$ in Figures 5 and 7). Theory therefore predicts a reasonable magnitude for the circulation $\Gamma$ generated by the advancing curtain.

The comparison between theory and observation confirms that viscous decay plays an important role in controlling the behavior of the flow in the ring vortex. First, a good match exists between estimates of the vortex core radius obtained from the RTM and observation. Second, the observed wind velocities (from the Styrofoam tracers) and the flow velocities estimated by the turbulent flow model behave similarly, decreasing in time as expected by viscous decay. Third, the constant outward velocity of the ring vortex during stage II results from expected viscous flow behavior. The large height of the ring vortex with respect to its core radius and the short time since the curtain became permeable minimizes viscous decay effects upon the advancing velocity of the ring vortex. Fourth, the reduction in outward velocity of the vortex core at late time ($t/T > 3-4$) reflects how viscous diffusion reduces the strength of the flow in a turbulent decaying vortex well after its creation. In the turbulent model estimates, the velocity reduction results uniquely from viscous diffusion in the ring vortex. In reality, both viscous diffusion and surface shear stresses contribute to velocity decay.

The expansion of the radius of the vortex toroid seen both
in theory and observations demonstrate that the motion of the ring vortex is self-induced. For a self-induced vortex, the magnitude of the expansion velocity of the ring vortex depends (besides viscous decay) on the height of the vortex core center. During stage II, because the vortex height is large and varies only slightly (first increasing and then decreasing immediately after S in Figure 5), the velocity of the vortex remains constant. The acceleration of the core of the ring vortex at the beginning of stage III reflects its decrease in height (Figure 5).

**Turbulent flow in the ring vortex.** Observations provide evidence that the flow in the ring vortex is turbulent. First, the RTM best fits the observed growth of the ring vortex while being physically the most reasonable. A laminar flow model, which also conserves both kinetic energy and momentum (RLM), predicts a vortex radius that reduces in size as function of time (see Figure 6), a result never observed in any of the impact experiments. Although the other laminar flow models also predict ring vortex growth, it is not significant compared to observation. Second, observed wind velocities at the surface generally match estimates for the turbulent flow models. And third, the turbulent flow models predict a stage IV in the outward motion of the ring vortex consistent with observations for some of the data. The laminar flow models, however, generally predict an increase in the outward motion of the ring vortex during stage IV; this is not observed.

The observation that the velocity in the ring vortex is turbulent agrees with observed turbulent ring vortices generated by an accelerating piston [Sallet and Widmayer, 1974]. Such a piston is roughly analogous to a decelerating ejecta curtain just before completion of crater growth.

It is important to determine whether the flow present in the ring vortex is laminar or turbulent, since the choice affects the lifetime of the winds created by an advancing ejecta curtain. This is especially significant in future studies where we wish to examine how curtain generated ring vortices control the final ejecta emplacement process.

**Theoretical and observational differences and their implications.** Several differences also exist between the theoretical predictions and observations (Figures 6, 7, 8 and 9). The observed radius of the core of the ring vortex and the outward motion of the Styrofoam tracers are slightly less than that predicted by the turbulent flow theory but significantly greater than that predicted by the laminar models. Furthermore, the observed outward velocity of the ring vortex core exceeds that estimated by the turbulent flow models, after \( v/T \sim 3 \), but is less than estimated by the laminar ones. All these results indicate that the turbulent models predict excessive decay of the flow in the ring vortex; however, the laminar flow models estimate too little decay.

The assumptions used in calculating the outward motion of the ring vortex further enhance the difference between the turbulent flow models and the observations after \( v/T \sim 3 \). We assume that once the calculated radius of the ring vortex exceeds the vortex height from the target, the vortex remains at a height equal to its core radius. This assumption avoids the unphysical situation where the edge of the vortex core exists underground. Figure 5 shows how this assumption causes the vortex to travel at a height exceeding that observed in the experiments after \( v/T \sim 3 \). The theoretically estimated velocity of the ring vortex becomes significantly less than observed after this time (Figure 8). This assumption therefore amplifies the effect of excess viscous decay predicted by the turbulent flow models.

The small difference after \( v/T \sim 3 \) between the laminar theory and observations for the outward motion of the ring vortex is not realistic because its motion is estimated from the observed height of the ring vortex. This estimate maintains the laminar ring-vortex core at a height greater than the radius of the vortex core calculated by the laminar flow models, a height that is contrary to both experimental and theoretical expectations. Indeed, the self-induced motion of the ring vortex should move it downward to within at least one vortex core radii from the surface [Magarvey and MacLetchly, 1979; Sheriff and Leonard, 1992]. Because the outward velocity of the ring vortex core varies inversely with distance from the target surface, the outward motion estimated by the laminar flow models in Figure 7 is slower than expected for a truly laminar ring vortex. Therefore, artificially maintaining the laminar ring-vortex core at the height observed in experiments reduces from the point of impact the run-out distance of the ring-vortex core as a function of time.

**Additional physical processes.** The small but apparent differences between the theory and observations occur because two physical phenomena of secondary importance also affect the flow in the ring vortex: first, the containment of the ring vortex by the particle flow in the adjacent ejecta curtain and, second, the compression of the ring vortex as it pushes itself against the target surface.

Immediately after the curtain becomes permeable, the core of the ring vortex continues to move upwards while it is near the curtain (immediately after S in Figures 5 and 10). This upward motion of the ring vortex results from the drag created by the upward trajectory of the ejecta particles at the inner surface of the ejecta curtain. Unlike the simplified theory that estimates the free growth of the ring vortex, the close proximity of the curtain causes the vortex growth to stagnate (Figure 10). The upward motion of the ejecta particles in the adjacent curtain could be offsetting viscous diffusion and growth of the vortex. This curtain effect on the vortex becomes less pronounced as the distance between the curtain and ring vortex increases. Eventually, the vortex moves downward by its self-induced motion, and the vortex radius grows independently as assumed in the theory. This usually occurs for \( v/T \) ranging between 2 and 3.

Once at the surface, the expansion of the vortex core subsides slightly more rapidly than expected by the RTM (Figures 6 and 10). The force of the self-induced flow compressing the vortex at the target surface deforms the shape of the ring vortex into an ellipsoid with its long axis parallel and its short axis perpendicular to the surface. In contrast with theory, such deformation reduces the average growth of the ring vortex, thereby preventing further free viscous decay (Figure 6).

It is important to emphasize that the differences between the theory and observations are small. They are the result of the second-order effects, which slow viscous decay when compared to the turbulent flow models. The RTM accurately models the first-order behavior of the ring vortex as exemplified by successful comparison between theory and observations for the generation, growth, and flow velocities of the ring vortex. The turbulent theory also reproduces the observed outward motion of the ring vortex until \( v/T \sim 3 \), after which the assumptions used in calculating the outward position of the ring vortex amplify the excess viscous decay predicted by the turbulent flow models. These results indicate that the physical processes of flow separation, self-induced motion, and turbulent viscous decay control the behavior of and the flow in the ring vortex.
Implications. The confidence gained by the comparison between theory and experiment allows one to establish the importance of curtain driven winds during planetary impact events. Such winds entrain ejecta below a critical size, thereby affecting styles of ejecta emplacement. For this purpose, we consider small craters whose impermeable ejecta curtain does not exceed the scale height of the atmosphere. Three simplifying but justifiable assumptions are then made as well. First, we use the incompressible start-up model, since the flow velocity at the point of flow separation remains below a Mach number of 0.4 to 0.6 for craters up to 30 km in diameter. Second, we assume that the curtain becomes permeable at the time of crater formation and that its length is equal to the crater radius. And third, we assume ambient atmospheric conditions based on previous arguments that late-stage ejecta emplacement will not be significantly affected by early-time disturbances [Schultz and Gault, 1979, 1982; Schultz, 1992a,b]. Although elevated temperatures (and reduced atmospheric densities) decrease the affected ejecta size, these conditions do not affect either the process of flow separation or the formation of a ring vortex behind the advancing ejecta curtain.

Three forces act upon an ejecta particle at the top of the impermeable portion of the ejecta curtain just when the curtain becomes permeable (1) atmospheric drag due to the ballistic motion of the ejecta, (2) atmospheric drag due to the winds separating of the top edge of the curtain, and (3) gravitational pull (Figure 11). Balancing these forces permits one to estimate the maximum ejecta particle diameter that will be entrained out of the curtain by curtain generated winds. Ejecta entrainment by winds derived from the top of the ejecta curtain will not significantly reduce the entrainment capacity of these winds when the curtain first becomes impermeable. On Venus, these winds carry ejecta up to 2 m for a 10 km apparent (precollapse) crater diameter and up to 8 m for a 30 km apparent crater diameter (45 km rim diameter after collapse). Smaller craters on Venus, however, are more likely affected by...
Atmospheric drag due to particle motion

Figure 11. Sketch of forces affecting particles at the top of the ejecta curtain when the curtain becomes permeable. By balancing these forces, we can determine the maximum ejecta particle diameter that will be entrained by the curtain-generated winds (see text).

The disturbed atmosphere created by the initial shock. On Earth, the ejecta entrained ranges between 2 mm for a 0.2 km apparent crater diameter to 20 cm for a 30 km apparent crater diameter (Figure 12). On Mars, such winds carry sand to pebble sized ejecta up to 200 \( \mu \text{m} \) for a 0.2 km apparent crater diameter and 5 mm for a 30 km apparent crater diameter. The estimates for Mars are a factor of 10 greater than previous first order estimates for entrainment based solely on estimates of curtain velocity [Schultz and Gault, 1979; Schultz, 1992a].

Our model now includes flow separation at the top of the impermeable curtain which accelerates the flow impinging upon the curtain.

On Mars and Venus, calculations show that by the time of crater formation most of an ejecta curtain will be surrounded by atmosphere at ambient atmospheric pressures [Schultz, 1992b]. However, the temperature and hence density of the atmosphere may not recover from the initial impact shock by this time. Figure 12 shows the effect of increasing the ambient temperature by a factor of 100 on the size of ejecta entrained. On Venus, the entrained ejecta diameter still represents pebble-sized debris (from 2 to 3 cm for craters ranging from 10 to 30 km in apparent crater diameter). On Mars, the maximum diameter of ejecta entrained represent sand-sized debris (from 100 \( \mu \text{m} \) to 800 \( \mu \text{m} \) for craters ranging from 0.2 to 30 km in apparent crater diameter). On Earth, presented results assume that the atmospheric pressure also has recovered by the time of crater formation. For these conditions, entrained particles range from 200 \( \mu \text{m} \) to 5 mm for craters ranging from 0.2 to 30 km in apparent crater diameter. In reality, the atmospheric pressure recovers by winds that accelerate inward toward the crater [e.g., Schultz, 1992b], thereby actually enhancing the winds created by the displacement of ambient atmosphere by an advancing ejecta curtain.

The above estimates for entrained ejecta diameters are probably conservative because they represent ejecta entrained directly from the top of the impermeable curtain (Figure 11). The winds in the core of the ring vortex are stronger than those at the top edge of the curtain, and potentially can transport larger ejecta from the backside of the curtain. Similarly, larger particles from the target surface can be transported because they are subject to (1) winds whose velocity sums the flow velocity in ring vortex and the lateral velocity of the expanding ring vortex; and (2) saltation by ejecta already entrained in the winds [Schultz, 1992a]. Ejecta entrained in curtain-derived winds may offset increases in their entrainment and carrying

Figure 12. Diameter of ejecta particles carried by curtain-generated winds as a function of apparent crater diameter on Mars, Earth, and Venus for ambient (top) and reduced atmospheric densities (bottom). Actual crater rim-diameters require a factor of 1.5 increase in size (true only for craters larger than 5-10 km on Mars). The length of the impermeable curtain does not exceed the atmospheric scale height of each respective planet. The limited range of crater diameters minimizes the effects of compressible flow effects (see text). Flow separation and a vortex sheets also should occur, however, when compressibility becomes important for more rapidly moving ejecta curtains of larger craters. For these calculations, the curtain becomes permeable at the time of crater formation and the curtain length is equal to the crater radius. The two atmospheric densities used reflect (1) ambient surface conditions and (2) higher postimpact temperatures possible in the postimpact environment (assuming a factor of 100 increase in temperature). Even under reduced atmospheric density curtain-driven winds are significant during an impact process. The jump in particle diameters for the Earth reflects changes in the drag coefficient of a sphere as a function of Reynolds number.
capacity because ejecta within curtain-derived vortices should reduce their flow velocity more rapidly than by atmospheric viscous diffusion and target shear drag alone.

The large ejecta that curtain-driven winds can entrain even when the atmosphere is heated suggest that such winds most likely play an important role in the ejecta entrainment and deposition process on planets with atmospheres. Results suggest that on present-day Mars where the atmosphere is tenuous, ejecta entrainment and deposition as described by Schultz and Gault [1979, 1982] and Schultz [1992a, b] is likely to occur. The calculations show that even terrestrial craters as small as Meteor Crater in Arizona should possess some evidence for ejecta entrained and emplaced by the interaction between the ejecta curtain and the atmosphere [Schultz and Gault, 1979; Schultz and Grant, 1989, Schultz and Anderson, 1996].

Concluding remarks

Comparison between experiments and theory indicates that the start-up vortex model provides a physically reasonable magnification for the circulation created by an advancing impermeable ejecta curtain. After the curtain becomes permeable, the general behavior of the ring vortex is attributed to turbulent flow in its core. Turbulent flow models (in particular, the RTM) reproduce the growth of the ring vortex, the outward motion of the ring vortex before \( t/T = 3 \), and the winds (flow velocity) of the ring vortex at the target surface. Although the turbulent models underestimate the general run-out of the ring vortex after \( t/T \sim 3 \), such models reproduce the general behavior of the motion of the observed ring vortex. The laminar models are far less satisfactory in reproducing critical aspects of the ring vortex.

Small differences between the theory and the experiments arise because the theory does not take into account shear drag acting on the established ring vortex by the ejecta moving upward along the inner surface of the curtain. Nor does it include the average reduction in growth of the ring vortex as it pushes itself against the target surface. Both effects restrict the growth and thus the decay rate of the ring vortex when compared with turbulent theory.

This study demonstrates that curtain-driven winds possess significant ejecta entrainment capacity and should play a significant role in the emplacement of ejecta on planets with atmospheres. The model results indicate that many of the atmospheric processes responsible for ejecta entrainment, transport, and deposition at laboratory scales very likely help create the ejecta morphology of planetary craters. Future studies will assess more completely the entrainment of ejecta by winds created during largescale impacts in different atmospheric environment. Such studies will analyze the atmospheric and physical parameters which control the time at which the ejecta curtain becomes permeable and will consider craters larger than 30 km in diameter by including the effects of supersonic flow separation and a stratified atmosphere. These studies will also consider mechanisms by which a ring vortex dissipates due to either ejecta entrainment, viscous diffusion or surface shear drag to assess to what extent impact-derived atmospheric vortices control ejecta emplacement processes and to what extent turbidity type flows derived from these vortices control ejecta emplacement.

Appendix

To estimate the effect of the outward expansion of the core of the ring vortex upon the flow velocity in the ring vortex, we first consider the laminar Oseen line vortex:

\[
V_\theta = \frac{\Gamma}{2\pi r} \left( 1 - e^{-\frac{r^2}{4\nu(t-t_i)}} \right)
\]  

where \( V_\theta \) is the axial flow velocity in the vortex; \( r \) is the distance from the center of the core of the ring vortex; \( \nu \) is the kinematic viscosity; \( t \) is time since impact; \( t_i \) is the time taken by the Oseen line to reach the radius of the ring vortex established when the curtain becomes permeable. The circulation \( \Gamma \) is replaced by \( \Gamma' \) in order to facilitate computations:

\[
\Gamma' = \Gamma \left( 1 - e^{-\frac{r^2}{4\nu(t-t_i)}} \right)
\]

The energy \( E \) in the ring vortex is given by

\[
E = \frac{1}{2} m V_\theta^2
\]

where \( m = 2 \rho \pi r^2 R \) is the mass in the torus constituting the ring vortex, \( \rho \) is the density of the fluid in the ring vortex, \( R \) is the radius of the ring vortex from the center of the core of the vortex to the center of the impact. Combining (A2) and (A3), the energy of the flow in the ring vortex at the time the curtain becomes permeable is given by

\[
E_0 = \frac{\rho \Gamma'_0 R_0}{4 \pi}
\]

The subscript 0 pertains to the time when the curtain becomes permeable and the ring vortex is first allowed to decay freely. After the ring vortex expands, equation (A4) takes the form

\[
E_n = \frac{\rho \Gamma'_n R_n}{4 \pi}
\]

where the subscript \( n \) implies conditions after the curtain and ring vortex decouple. Other than the losses of energy due to viscous diffusion that are already included in the formulation of the Oseen line vortex, \( E_n \) and \( E_0 \) must equal each other in order to conserve energy. The new circulation \( \Gamma'_n \) in the ring vortex therefore must take the form

\[
\Gamma'_n = \Gamma'_0 \sqrt{R_0/R_n}
\]

Conserving energy in the ring vortex, therefore, tends to enhance the decay of the circulation, i.e. to reduce the velocity of the flow in the ring vortex. If the angular momentum \( H \) in the ring vortex is conserved as the ring vortex expands, the momentum becomes
\[ H_0 = m \left( r \times \mathbf{v}_0 \right) \]
\[ = \rho r_c^2 R_0 \Gamma_0 ' \]  

(A7)

when the curtain becomes permeable. The variable \( r_c \) is equal to the radius of the core of the ring vortex. Again, the subscript 0 pertains to the time when the curtain becomes permeable. After the ring vortex moves outward, the ring vortex possesses a new angular momentum

\[ H_n = \rho r_{cn}^2 R_n \Gamma_n ' \]  

(A8)

Conservation of angular momentum requires equating equations (A7) and (A8). Substituting equation (A6) for \( \Gamma_n ' \) defines the new radius \( r_{cn} \) of the core of the ring vortex:

\[ r_{cn} = r_c \left( \frac{R_0}{R_n} \right)^{1/4} \]  

(A9)

Conserving angular momentum in the ring vortex therefore causes its core radius to decrease and must increase the flow velocity in the ring vortex. Meanwhile viscous diffusion will cause the core of the ring vortex to expand, i.e. increasing \( r_c \) by 2.245 \( \sqrt{\nu t} \). Therefore, \( r_{cn} \) is actually given by

\[ r_{cn} = 2.245 \sqrt{\nu (t - t_i)} \left( \frac{R_0}{R_n} \right)^{1/4} \]  

(A10)

In order to evaluate the combined effects of viscous diffusion, conservation of angular momentum and kinetic energy in the ring vortex, we replace \( r_{cn} \) with 2.245 \( \sqrt{\nu (t - t_i)} \) where \( t_n \) is the time that takes into account the effect of conserving the angular momentum in the ring vortex. This variable becomes

\[ t_n = (t - t_i) \left( \frac{R_0}{R_i} \right)^{1/2} + t_i \]  

(A11)

Substituting (A11) and (A6) into (A1), we find that the Oseen line vortex which maintains kinetic energy and angular momentum is given by

\[ \mathbf{v}_0 = \frac{\Gamma}{2\pi r} \left( \frac{R_0}{R} \right)^{1/2} \left( 1 - \frac{r^2}{4\nu (t_i)(R_0/R)^2} \right) \]  

(A12)

The conservation of angular momentum therefore reduces the denominator in the decay term of the ring vortex. Consequently, the axial velocity is higher in the ring vortex than if it decayed freely. Conservation of angular momentum offsets the effects of the conservation of kinetic energy and viscous diffusion, which reduces the circulation and hence the axial flow velocity in the ring vortex as the ring vortex moves outward.

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O. Barnouin-Jha and P. H. Schultz, Department of Geological Sciences, Box 1846, Brown University, Providence, RI 02912.

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