A CONTINUUM MODEL FOR ATMOSPHERIC RESPONSE TO AN ADVANCING EJECTA CURTAIN. O. Barnouin and P. H. Schultz. Dept. of Geological Science, Brown University, Providence, R.I.

Introduction: Crater excavation creates large quantities of debris to form an impermeable continuous ejecta wall that moves forward through the atmosphere, thereby inducing a response wind [1,2]. As long as the density of the ejecta curtain is large with respect to the surrounding atmosphere, the curtain resembles an inclined flat plate interacting and displacing the atmosphere as it moves. Such interactions can be modeled to first-order by inviscid flow theory. The resulting flow produces a circulation at the leading edge of the curtain that entrains sufficiently small ejecta as energy density in the curtain reduces with time. Aerodynamic drag acting on individual ejecta curtain coupled with the curtain-generated circulation controls the amount of ejecta entrained and the size distribution of the particles it can carry. The turbulent power generated by the circulation associated with the entrained ejecta fraction ultimately forms turbidity flows with long run-out distances [1, 2].

The Model: The ejecta curtain is viewed as an ensemble of particles, each individual particle moving as a stream on ballistic paths during crater growth. Ejection velocities of each particle at a given time (or stage of growth) have characteristic values given in [3]. The locus of these particles defines the ejecta curtain inclined at about 45° to the target surface where the horizontal velocity of the curtain is tied to the horizontal velocity of the crater growth.

If a planetary atmosphere is viewed as an incompressible Newtonian fluid, the flow generated in front of the ejecta curtain can be described by an inviscid corner flow model. This model permits evaluating the velocity and pressure fields in front of the curtain, whereas the velocity distribution in the ejecta allows calculating the Reynolds number and the boundary layer thickness of the flow. Values for the thickness of such a boundary layer are obtained for steady-state flow conditions, a good approximation for high speed flows along a surface [4].

The circulation about the ejecta curtain is obtained by assuming the Kutta-Joukowski condition where a stagnation point must exist at the leading edge of the plate. This necessitates a circulation proportional to the velocity and length of the plate. Its magnitude must suffice to move one of the stagnation points predicted to be present by inviscid flow theory when no circulation exists to the new position at the upper end of the ejecta curtain. According to Batchelor [5], the Kutta-Joukowski hypothesis should predict to first-order the nature of the circulation for flow about a 180° corner, and, thus, should provide a reasonable estimate of the circulation about the leading edge of the ejecta curtain.

Discussion: This relatively simple model allows estimating the magnitude of the circulation produced at the leading edge of an ejecta curtain. Figure 1 shows that this circulation is quite large for a 10 km crater on Mars as well as on the Earth and Venus. This was found to be equally true for 2 km craters. Table 1 indicates that minimum circulation winds approach hurricane strength for a vortex whose radius equals the maximum coherent length of the ejecta curtain. In reality, these vortices will be smaller than the scale of the maximum extension of the curtain; therefore, the circulating winds noted in Table 1 are lower limits. Entrainment occurs once sufficiently small ejecta are decelerated by drag to velocities. Since the magnitude of the circulation approach ejection velocities for 10 km-diameter craters in Table 1, the ejecta fraction potentially entrained in the atmospheric response becomes significant.

The relative magnitude of the circulation and the velocity of individual ejecta determines the size of the particles entrained. For large circulations such as on Earth and Venus, the largest particles suspended by the circulation approach meters in size. Since the circulation on Venus is slightly smaller than on Earth, one could expect that the size of the large ejecta entrained on Venus will be smaller than on Earth. However, due to the large difference in atmospheric density between the two planets, the size of this ejecta will actually be larger on Venus than on the Earth. On Mars, where the circulation is about half that of the Earth's and Venus', the largest particles entrained by the circulation will measure centimeters once their ballistic velocities approach the circulation velocities. These predictions are for small craters produced in the gravity-controlled regime.

As discussed in [1], the degree of entrainment and turbulent power in curtain-induced vortices control the run-out distance of the resulting flow once it separates from the ballistic curtain. The turbulence-suspended flow results in small ejecta sizes extending to large distances in contrast with expectations from simple aerodynamic drag acting on ballistic trajectories [6]. Because the circulation deposits large particles first as its kinetic energy dissipates, the most distal facies should exhibit the smallest size fraction. Nevertheless, even large ejecta may be carried to much greater distances than expected.

Dissipating forces due to the kinematic viscosity of the atmosphere acting directly upon the circulation winds play an important role in determining the total distance the ejecta runs out. Viscosity of the
surrounding atmosphere will act to slow down the velocity of the winds generated by the circulation once it is established. Dissipation of its turbulent strength reduces the distances at which ejecta deposition occurs. To first-order, the magnitude of the circulation varies inversely with atmospheric kinematic viscosity \( \nu \). Using the results obtained from the above model, and taking into account this viscous effect one can qualitatively assess the relative limit of ejecta deposition for Mars, Venus and Earth. For a low viscosity planetary atmosphere such as on Mars \( (\nu = 1.1 \times 10^{-5} \text{ Ns/m}^2) \) the ejecta deposition distance will be large even though the circulation generated here is small. For the high viscosity atmosphere of Venus \( (\nu = 3.3 \times 10^{-5} \text{ Ns/m}^2) \) the ejecta deposition distance will be small in comparison with the magnitude of the circulation, and, therefore, size of the crater responsible for the circulation. On Earth \( (\nu = 1.8 \times 10^{-5} \text{ Ns/m}^2) \) the atmospheric viscosity is relatively small while the circulation is large. Hence, deposition distance is large but will be less than on Mars for a similar amount of circulation.

The circulatory behavior of the atmosphere as predicted by the model can be directly verified with laboratory experiments performed at the NASA Ames Vertical Gun. The model predicts that a bulge of increased turbulence exists in the boundary layer at those places where the velocity of the atmospheric flow equals that of the particles in the curtain. This has the net effect of producing a stagnation point that will move up along the ejecta at early time. This stagnation point is essentially a region of induced drag vorticity that has been observed in laboratory experiments [1, 6]. Such phenomena as well as observed patterns of circulation should allow specific quantitative tests for the model. Since inviscid flow theory is independent of scale (as long as the fluid remains incompressible), the model validated at laboratory scale should provide insight for processes at planetary scales. The condition of incompressibility is valid for most portions of the fluid accelerating along the ejecta. As scale increases, however, the flow along the ejecta curtain will reach the speed of sound of the atmosphere over a greater fraction of crater growth. Nevertheless, this should not significantly lessen the effects of the circulation at later times.

**Conclusion:** The solid plate model for an ejecta curtain moving through the atmosphere provides first-order estimates and predictions of the atmospheric response. The magnitude of the derived circulation suggests that large portions of the ejecta below a critical size can be entrained thereby affecting ejecta run-out and deposition distances.

**References:**

Table 1: Minimum circulation winds produced by a 10 km on three terrestrial planets

<table>
<thead>
<tr>
<th>Circulation winds for a crater with a 5 km radius on</th>
<th>Hurricane winds</th>
</tr>
</thead>
<tbody>
<tr>
<td>Earth</td>
<td>Mars</td>
</tr>
<tr>
<td>105.11 m/s</td>
<td>25.01 m/s</td>
</tr>
<tr>
<td>123.06 m/s</td>
<td>54.70 m/s</td>
</tr>
</tbody>
</table>

Maximum and minimum values for the circulation winds were calculated using circulation values obtained after the curtain reached its maximum length.