BEHAVIOR OF VORTICES GENERATED BY AN ADVANCING EJECTA CURTAIN IN THEORY, IN THE LABORATORY, AND ON MARS. O.S. Barnouin and P.H. Schultz, Dept. of Geological Sciences, Brown University, Providence, R.I. 02912.

Introduction: Several papers [1, 2, 3, 4] assess the interaction between an atmosphere and advancing ejecta to assess possible atmospheric processes affecting ejecta emplacement. Ejecta travel through an atmosphere in two modes [1]: larger ejecta blocks follow ballistic trajectories unhindered by the atmosphere; finer ejecta are entrained in a turbulent basal cloud, which develops as the advancing ejecta curtain generates strong atmospheric winds. Laboratory experiments [1, 2, 3] reveal that this cloud of fine ejecta produce ramparts, flow lobes, or radial scouring that superposes larger ballistic ejecta emplaced earlier. Martian [1, 2, 3], Venusian [4, 5] and terrestrial ejecta facies [1, 6] can be interpreted in terms of processes observed in the laboratory with appropriate first-order corrections for scaling. A continuum model [7] of the atmospheric flow around an advancing inclined plate simulated and reproduced some of the complex flow patterns observed in front and at the top of the curtain [3]. Here we consider improvements to the model to compare quantitatively the approximate position of ejecta deposition (i.e. run-out distance) with laboratory experiments and martian ejecta facies.

Theory: At the time of crater formation, the bulk of the ejecta comprises a relatively thin ejecta wall forming an inclined curtain [8]. Since shock processes and comminution during excavation [9] ensures that a large fraction of this ejecta is small with respect to the curtain width, the base of the curtain forms an impermeable wall with respect to the atmosphere. As a consequence, the atmosphere sees the ejecta curtain as a continuous plate-like structure in the laboratory and on Mars [3]. A Kutta-Joukowski estimate [6] allows calculating the circulation generated by this analogy with the advancing curtain. The circulation must generate two vortices to conserve angular momentum in the atmosphere in the vicinity of the curtain as it decelerates to its minimum velocity at the end of crater excavation. A stronger flow separation vortex occurs below, behind the continuous portion of the curtain. If the curtain moves from left to right, then this lower vortex rotates in a counterclockwise direction with a circulation greater than the circulation generated by the ejecta curtain at a given time, reflecting remnant angular momentum from an earlier time. A second vortex shed at the top of the continuous curtain rotates in the opposite direction, with a circulation equal to the difference between that generated by the advancing curtain and the lower vortex. The strength of this upper vortex increases until the ejecta curtain reaches its minimum speed. As the curtain starts accelerating again [3], angular momentum is no longer supplied to the upper vortex; hence, it dissipates by diffusion. The lower vortex, however, regains the strength previously lost until the curtain becomes discontinuous, i.e. permeable to the flow. At this point, vorticity generated at the base of the curtain within the boundary layer [6] interacts with the vortex generated behind the curtain, thereby perhaps strengthening still further. This vortex entrains the finer grain fraction of the thinning ejecta curtain and proceeds outwards, driven by the horizontal momentum imparted to it by the curtain but losing strength by diffusion.

For an incompressible flow, each vortex generated by the curtain is described by the vorticity equation

$$\frac{D\omega}{Dt} = \omega\nabla\mathbf{v} + \nu\nabla^2\omega$$

rate of change of vorticity = rate of deformation of the vortex lines + net rate of viscous diffusion

where ω is the vorticity vector of the flow, $\mathbf{v}$ is the velocity vector of the flow, and ν is the kinematic viscosity. This equation does not entirely describe the behavior of the vorticity in a stratified incompressible flow. An additional term is required because the center of mass of a fluid particle in a density gradient does not coincide with its geometric center. Since pressure acts through this point, the fluid parcel should rotate, producing additional vorticity affecting large scale vortices. For simplicity, such effects are not considered. Although an axisymmetric geometry is assumed, the vortices shed by the ejecta curtain are viewed as two dimensional. These simplifying assumptions yield the vorticity diffusion equation:

$$\frac{D\omega}{Dt} = \nu\nabla^2\omega$$

Considering the flow in the vortex to be irrotational, then a solution of this diffusion equation is the Oseen vortex:

$$v_\Theta = \frac{\Gamma}{2\pi r}(1-\exp(-r^2/4\nu t))$$

where v_Θ is the angular flow velocity, r is the radius from the vortex center, Γ is the circulation of the vortex and t is time. Such a model has been used effectively to determine the decay of laminar vortices and, with some modification, large scale turbulent vortices shed behind airfoils [10, 11].

Aerodynamic forces decelerate individual ejecta to a velocity where they are entrained in the Oseen vortex. The maximum particle size that the vortex entrains is determined simply by equating the weight of a spherical body to the drag force generated by v_Θ, the flow velocity in the vortex.

Laboratory: Laboratory experiments performed at the NASA Ames Vertical Gun Range verify both qualitatively

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[2,3] and quantitatively [6] the theoretical justification for the flow generated by the advancing ejecta curtain. At the time of crater formation, two vortices are observed, and as expected, a weaker, short-lived vortex forms at the top of the curtain. The stronger vortex forms behind the base of the curtain and gains strength once the ejecta curtain accelerates outwards beyond the crater rim [1, 2, 3].

At low pressures (0.06 bar atmosphere), most ejecta are ballistically emplaced for a crater formed in pumice by a projectile travelling at 2 km/s, but the atmosphere entrains a small fraction of the ejecta. Because the pumice target has a bimodal grain size distribution, with peaks at 80 μ and 25 μ [3], a subtle rampart is produced. Application of the Oseen vortex suggests the vortex winds should carry the 80 μ particles for 0.25 times the total time of crater formation (38 ms), provided that these particles are sufficiently decelerated for entrainment by the maximum circulation generated by the curtain. The 25 μ particles, if entrained, will be carried for only a slightly longer time (98 ms). The theoretical results are therefore consistent to first order with observations.

The Oseen vortex also can be used to determine the time at which both the 80 and 25 μ pumice particles are deposited over a range of atmospheric pressures and densities. Multiplying the theoretical time of deposition by the outward velocity (from the film record) provides a first-order estimate of the ejecta run-out distance. This approach provides a consistent match between theory and experiments, thereby establishing confidence for extrapolation to broader scales.

Planetary scales: Several conditions must be met for the above model to apply at martian scales. First, the model requires that the flow around the continuous portion of the ejecta curtain remains incompressible. Thus, the velocity of this curtain must be subsonic at the time of crater formation. This condition is true for Mars for craters up 100 km in diameter [2, 3]. Second, the atmosphere needs to recover from the initial impact blast by the time of crater completion. On Mars, the pressure satisfies this requirement as it returns to ambient conditions well before crater formation [3, 4]. Third, turbulent flow enhances viscous diffusion in the vortices generated at large scales and requires that the viscosity term ν in the Oseen vortex be replaced by an effective viscosity $\nu_{eff}=\nu+a\Gamma$. The constant a is determined empirically by observing the time for vortices shed by airfoils to diffuse together.

The flow-like nature of the inner ejecta facies for martian craters could be the result of water released during impact that decreases basal shear of the larger initially ballistically emplaced ejecta near the rim [3,12]. The Oseen vortex, therefore, is most relevant for the role of curtain generated winds controlling run-out distances of the outer ejecta deposits. The theory suggests that maximum winds (just below the speed of sound) carry particles up to 4 cm in diameter. However, because these maximum vortex winds rapidly decay by diffusion, this maximum particle size is entrained by the vortex flow for only a brief instant. From rim-to-rampart distances [3], preliminary analyzes indicate that if ramparts consist of 3 cm diameter particles carried by the vortex, then the basal vortex must have traveled outwards with a velocity approximately equal to the minimum curtain velocity at the time of crater formation. If the ramparts are made of smaller grain sizes, this velocity can be less. Theory, hence, suggests that curtain generated winds deposit finer ejecta after the larger ballistically emplaced ejecta, consistent with the observed depositional sequence on Mars [1, 2, 3, 12].

If we assume that the derived minimum velocity equals the expected outward vortex velocity in the present day martian atmosphere, then the Oseen vortex suggests that craters of similar sizes but with different run-out distances result from either, or the combination of two situations. If the run-out distance is greater than commonly expected from [3] then: 1.) the particles in the rampart or flow-lobe are smaller than 3 cm in diameter, the reference particle diameter; and/or 2.) the atmospheric density at impact is larger than today, possibly from impact released volatiles, a thicker atmosphere in the martian past, or both. For two side-by-side 5 km diameter craters in the Hesperian ridged plains (28.6 S, 241.9 W), similar target properties should result in common ejecta sizes assumed to equal the 3 cm reference diameter in the ejecta facies observed. However, one of the craters has thin distal lobes that extend to about 2.5 crater radii while the other has a contiguous rampart at the typical rim-to-rampart distance of 1.7-1.8 crater radii [3]. Application of the model suggests that the density of the atmosphere must have been close to 0.080 kg/m^3 when the first crater, but close to present day conditions at 0.018 kg/m^3 [13] for the second. This factor of 4 change in density and, hence, pressure could have resulted from precession-driven climate changes [3].

Conclusion: Although the Oseen vortex does not describe the final stages of ejecta emplacement in an atmosphere [3], it does provide a clue to the run-out distance before deposition of ejecta of different grain sizes in the laboratory. At large scales, the Oseen vortex model may provide information on either the grain size (i.e. local geology) or the atmospheric environment of the ejecta through time. However, the model has limitations: it does not include the effects of a stratified atmosphere; viscous diffusion in the core of the large vortices where the flow is supersonic; and, another process similar to a hydraulic jump but which occurs in vorticity, i.e. vortex breakdown.

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