ATMOSPHERIC ORIGIN OF FLOW LOBES AROUND CRATERS ON MARS AND VENUS.

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Distal flow lobes around craters on planets with atmospheres may result from the formation of waves in a ring vortex created by flow separation at the top edge of an advancing impact ejecta curtain [1,2,3]. The number of waves in a smoke ring is controlled by two factors: 1.) the ratio of the radius of the ring vortex (R_V) to its core radius (a); and, 2.) the intensity of the flow in the ring vortex core [4,5]. At laboratory scales, the number of ejecta flows from ejecta-driven ring vortices varies with these factors in the same fashion as waves of a smoke ring. Theoretical and laboratory studies indicate that the number of flow lobes created during an impact varies with the crater radius (R) to the three-fourths power (i.e. $R^{3/4}$). Lobe counts on Mars and Venus confirm this correlation for those craters whose radii do not exceed the scale height of the atmosphere and where the flow in the ring vortex does not exceed the ambient speed of sound. The formation of flow lobes by ring vortices created by the motion of the ejecta curtain, are consistent, therefore, with observation at planetary scales. Variations in the number of lobes on Mars could indicate variations in target lithologies, presence of volatiles or changes in atmospheric conditions. Further work will establish which of these contributing factors most affects the number of distal lobes created during an impact.

Background: A ring vortex sheet is created by flow separation at the top of the impermeable portion of an impact ejecta curtain as it advances through an atmosphere [1,2,3]. The vortex sheet becomes a vortex ring which entrains and carries sufficiently fine grained ejecta [1,2,3]. Such a vortex is analogous to a smoke ring in which instabilities create waves [4,5]. We investigate whether such waves create the conditions necessary for the formation of flow lobes at planetary and laboratory scales. Previous empirical studies attempt to link the number of lobes at Martian craters to either the presence of subsurface volatiles [6,7], or variations in atmospheric densities, and target lithology [8].

The number of waves generated in a ring vortex are the result of two parameters: 1.) the ratio of the radius of the ring vortex to its core radius, i.e. R_V/a; and 2.) the intensity of the flow in the core of the ring vortex [4,5]. The intensity of the flow in the ring vortex is given by the circulation Γ which we non-dimensionalize by dividing it by the kinematic viscosity, ν, to give the Reynolds number:

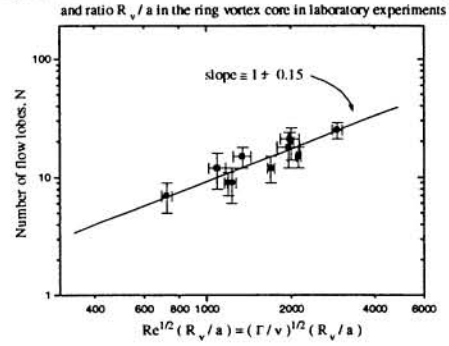
$$Re = \Gamma/\nu = \Gamma\rho/\mu. \qquad \text{Eq. I}$$

where ρ and μ are the ambient atmospheric density and absolute viscosity respectively. The number of waves N generated by the ring vortex is then found from [5] to be proportional to:

$$N \sim Re^{1/2}\,(R_V/a) = (\Gamma/\nu)^{1/2}\,(R_V/a). \qquad \text{Eq. II}$$

In order to test whether such a relationship applies to the impact derived ring vortices, we performed vertical impacts experiments at the Ames Vertical Gun Range in a fine grained target under a variety of atmospheric conditions. In order to estimate a and Γ, we used high speed video images (500-1000 f/s) to measure the length of the impermeable curtain, the curtain's velocity and the time when the curtain becomes permeable. With these parameters, Γ and a can be determined reliably from [9]. Also measured after each impact are the number of ejecta flow lobes created during each experiment. Figure 1 shows that the slope of N varies linearly with $Re^{1/2}\,(R_V/a)$ within experimental error as expected if the waves resulting from instabilities in the ring vortex control the number of flow lobes created during laboratory-scale impacts.

Figure 1: Measured number of flow lobes as a function of the flow intensity and ratio R_v/a in the ring vortex core in laboratory experiments



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Planetary Applications: Before extending laboratory results to planetary scales, we consider the limits of the theory. First, the estimates of a and Γ only apply when the flow in the ring vortex is subsonic [9]. Second, the winds created by the curtain may be affected by the scale height of the ambient atmosphere. Even when such conditions are not met, however, flow separation and the creation of ring vortex should still occur.

Early time impact phenomena probably do not significantly affect the vortices created by the late-stage advancing ejecta curtain. For Martian conditions, most early-time impact phenomena will have dissipated [3]. For Venusian conditions, the blast and vapor cloud region is contained by high atmospheric pressures within a crater radius and as result principally affects the ejecta curtain downrange [10,11].

If the impermeable length L of the curtain scales with R, equation II and scaling relations for crater formation time and ejecta curtain velocity [1,12] reveal that N varies proportionally with the crater radius R to the three-fourths power:

$$N \sim (\Gamma/\nu)^{1/2} (R_v / a) \sim A\, R^{3/4}\, g^{1/4} / \nu^{1/2}. \qquad \text{Eq. III}$$

where A is a constant and g is gravity. Measurements of N as function of crater radii for Venusian craters in basaltic plains and fresh Martian craters in Lunae Planum are consistent with the above theoretical and experimental expectations: specifically N on both two planets varies with crater radius to three fourths power ($R^{3/4}$; see Figure 2 and 3 below).

Figure 2: Number of flow lobes as a function of crater diameter on Venus. No correction for modification because all craters are complex

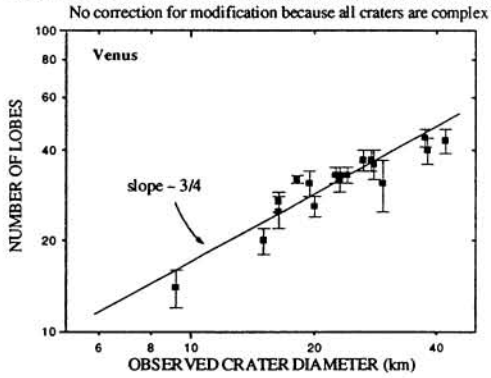
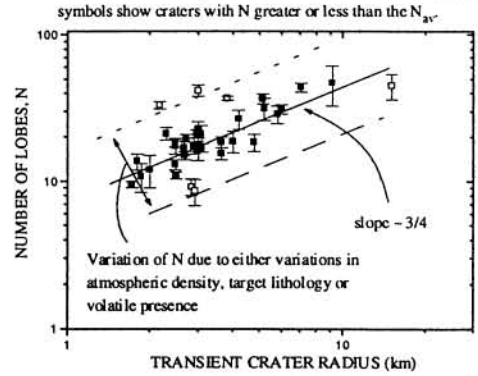


Figure 3: Number of flow lobes as a function of apparent crater radius on Lunae Planum, Mars. Complex craters are corrected for modification. Open symbols show craters with N greater or less than the N_{av}.



Implications: The above correlation between N and $R^{3/4}$ for ejecta flow lobes on both Venus and Mars are consistent with instabilities created in a ring vortex formed by an advancing impermeable ejecta curtain. Extending laboratory results to Venus craters indicates that a significant amount of entrainment occurs in the ring vortex at the time when the curtain becomes permeable (possibly 100-500 times increase in effective viscosity consistent with 40-50% particle volume fraction present in the ring vortex [13]). Furthermore, some heating of the ambient atmosphere (on the order of a few 1000 K) by the early time blast and vapor may be required.

Some Martian craters in Lunae Planum exhibit N that depart from the average N_{av}. Three factors could contribute to these variations: 1.) changes in the ambient atmospheric density (by as much as a factor of 25); 2.) local variations in target lithology; and 3.) possible entrainment of volatiles into the ring vortex. Further research will establish which of these contributing factors are the most important in controlling the number of lobes at Martian craters.

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