IMPACT VAPOR GENERATION INFERRED FROM RUN-OUT FLOWS ON VENUS. Seiji Sugita and Peter. H. Schultz; Brown University, Providence, RI 02912

Oblique impact craters on Venus are commonly associated with long run-out flows extending downrange. Parametric hydrocode calculations are used to assess the variables controlling the downrange off-set of the source region of such flows. We find that the impact-angle dependence of the downrange offset of the source region of the run-out flows measured from the point of impact can be readily explained by energy and momentum coupling efficiencies in the downrange impact vapor/melt.

Introduction: Impact vapor clouds strongly affects the environment of Earth [1, 2, 3] and Mars [4], where the atmosphere is very thin. But their direct geologic record is difficult to identify on these planets (but see [5]). The thick Venus atmosphere, however, can decelerate the expansion and translational motion of a downrange-directed vapor cloud [6]. The contained impact vapor is likely to condense and contribute to run-out flows that extends from certain craters [6, 7]. Thus, Venus is a natural large-scale impact laboratory that allows assessing the evolution of impact vapor. To interpret results of these "natural experiments", we compare observations with both numerical calculations and small-scale laboratory experiments.

Hydrodynamical calculations: We conducted series of numerical calculations over a wide range of parameters to understand the general hydrodynamical behavior of impact vapor clouds in the Venus atmosphere. The initial vapor cloud is assumed to be an ideal gas sphere with uniform density (1 - 8 g/cc), specific energy (25 - 100 MJ/kg) and downrange translational velocity (2 - 12 km/s) in the horizontal direction. The ambient Venus atmosphere is assumed to be an ideal CO_2 gas with uniform temperature (740°K) and uniform pressure (3 - 92 bar). Because of the geometric symmetry of the model vapor cloud, our two-dimensional hydrocode [7] was used with an axisymmetric coordinate system.

Fig. 1 shows the terminal temperature of impact vapor clouds for different initial downrange velocities, V_{tr}, and initial specific energies ε_{vap}, and indicates that if the initial specific energy is too large or if initial downrange velocity is too high, impact vapor does not condense. Although our hydrocode does not include radiational cooling, a simple analytical evaluation shows that its effect is too small to significantly affect a kilometer-size vapor cloud in the Venus atmosphere. This suggests that an impact vapor cloud created by a higher velocity impact (as well as volatile-rich impactors [6]) may leave uncondensed suspension flows extending downrange.

Fig. 2 shows the downrange total travel distance, L, of impact vapor clouds scaled by radius, r_p, of impactor. Note that the downrange total travel distance has a super-linear dependence on the initial downrange velocity. This results from dynamic reshaping of the vapor cloud during its downrange course [6]. The results of the parametric study can be summarized in the form of a semi-empirical scaling law:

$$\frac{L}{r_p} = 13\left(\frac{\rho_{air}}{67\mathrm{kg/m^3}}\right)^{\frac{1}{3}}\left(\frac{\rho_{vap}}{3\mathrm{g/cc}}\right)^{0.4}\left(\frac{M_{vap}}{M_{proj}}\right)^{\frac{1}{3}}\left(\frac{\varepsilon_{vap}}{50\mathrm{MJ/kg}}\right)^{-1}\left(\frac{V_{tr}}{10\mathrm{km/s}}\right)^{1.3} \tag{1}$$

where ρ_{air}, ρ_{vap}, M_{vap}, and M_{proj} are ambient air density, the initial density and the mass of impact vapor cloud, and the mass of projectile, respectively This scaling relation can be rewritten in terms of an energy coupling ratio, $\alpha \equiv$ (initial energy of vapor cloud)/(impact energy), momentum coupling ratio, $\beta \equiv$ (momentum of vapor cloud)/(momentum of impactor), and vapor mass ratio, $\psi \equiv M_{vap}/M_{proj}$:

$$\frac{L}{r_p} = 10\left(\frac{\rho_{air}}{67\mathrm{kg/m^3}}\right)^{\frac{1}{3}}\left(\frac{\rho_{vap}}{3\mathrm{g/cc}}\right)^{0.4}\psi^{0.03}\left(\frac{\alpha}{15\%}\right)^{-1}\left(\frac{\beta}{50\%}\right)^{1.3}\left(\frac{V_{im}}{25\mathrm{km/s}}\right)^{-0.7} \tag{2}$$

where V_{im} is impact velocity. Note the very small dependence of the vapor mass ratio, ψ.

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Venus: The observed downrange offset, L_{obs}, of the source region of run-out flows on Venus is assumed to represent the total travel distance of impact vapor cloud before becoming controlled by gravity [6, 7]. Observations [7] suggest that L_{obs}/r_p is proportional to $\cot^{\xi}\theta$ where θ is impact angle measured from the horizontal and $\xi = 1 \pm 0.3$. Laboratory experiments of oblique impacts [1] also show that the momentum coupling ratio, β, is proportional to $\cot^{\eta}\theta$, where $\eta \geq 0.7$ over a range of impact angle ($7.5° \leq \theta \leq 30°$). To match the observed angle-dependence ($\xi \approx 1$) of the downrange source region off-set on Venus, equation (2) requires that the energy-coupling ratio, α, of impact vapor cloud should be constant or increase with decreasing impact angle. If vaporization in an oblique impact is controlled only by shock heating within a hemispherical high-pressure region as in a near-vertical impact [8, 9], then the amount of internal energy coupled to the resulting vapor cloud should decrease with decreasing impact angle. This expectation is inconsistent with our analyses of run-out flows on Venus. Such a discrepancy may be explained by vaporization enhancement due to either shear heating or sibling impacts by shock decapitation of projectile [10, 11], because these processes are more efficient in lower angle impacts.

References: [1] Schultz, P. H. and Gault, D. E., *GSA Special Paper*, *247*, 239-261 (1990) [2] Alvarez, W. et al., *Nature*, *269*, 930-935 (1995) [3] Schultz, P. H. and D'Hondt, S., *Nature*, submitted (1996) [4] Melosh, H. J. and A. M. Vickery, *Nature*, *338*, 487-489, (1989) [5] Schultz, P. H., *LPSC abstract*, *26*, 1039-1040 (1988) [6] Schultz, P. H. *JGR*, *97*, 16183-16248 (1992) [7] Sugita, S. and Schultz, P. H., *LPSC abstract*, *26*, 1369-1370 (1995) [8] Gault, D. E. and Heitowit, E. D., *Proc. Sixth Hypervelocity Impact Symp.*, *2*, 419-456 (1963) [9] O'Keefe, J. D. and Ahrens, T. J., *Proc. 8th Lunar Planet. Sci. Conf.*, 3357-3374 (1977) [10] Schultz, P. H., *LPSC abstract*, *26*, 1249-1250 (1995) [11] Schultz, P. H., *JGR*, submitted (1996)

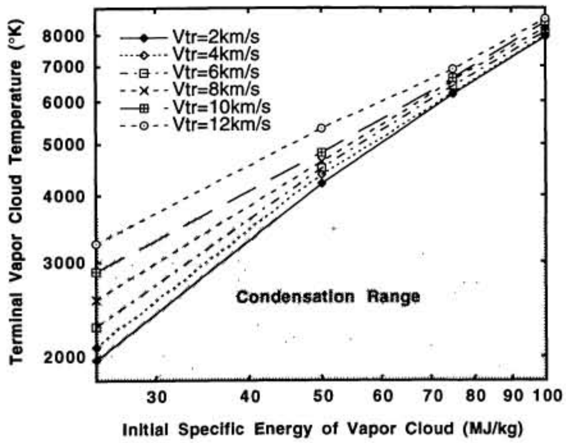

Figure 1. The terminal mean temperature of impact vapor clouds as a function of the initial downrange translational velocity and the initial specific energy of impact vapor clouds, including vaporization energy (12 MJ/kg). The initial density and mass of impact vapor clouds are assumed to be 3 g/cc and equal to projectile mass, respectively. The pressure of the ambient atmosphere is assumed to be 92 bar (Venus surface condition).

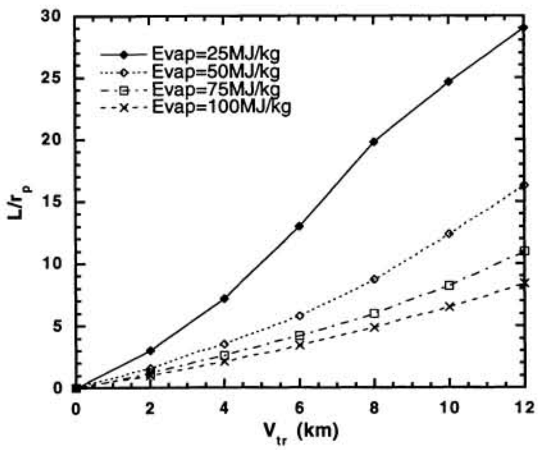

Figure 2. The total travel distance, L, of impact vapor clouds scaled by projectile radius, r_p, as a function of the initial downrange translational velocity, V_{tr}, and the specific internal energy, E_{vap}, of impact vapor clouds, including vaporization energy (12 MJ/kg). The calculation parameters are same as in Figure 1.