# Dynamical Evolution of Vapor Clouds by Oblique Impacts on Venus.

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Previous studies [1, 2] showed that an oblique impact generates a ballistic vapor cloud that moves downrange and is physically decoupled from the late excavation stage of cratering. The initial downrange translational motion is strongly controlled by the impact angle, whereby lower impact angles (measured from horizon) result in a higher downrange velocity. This study theoretically describes the dynamics of such impact vapor clouds on Venus in order to assess their possible signatures in the geologic record.

**Hydrodynamic Calculations:** We have constructed a two-dimensional hydrocode based on CIP (Cubic Interpolated Pseudoparticle) method, which has been successfully applied to various kinds of hydrodynamic problems [3]. The initial vapor cloud is assumed to have a circular shape with a radius of 1 km, density of 3 g/cc, internal energy of 28 MJ/kg, and initial downrange translational velocity of 5 or 8 km/s. The initial internal energy corresponds to a 1km-radius object impacting the surface of Venus at 18 km/s and partitioning 25% of the initial kinetic energy into vaporization (including 12 MJ/kg for the phase transition). The ambient Venus atmosphere is assumed to be an ideal $CO_2$ gas with temperature of 740°K and pressure of 92 bar. Planar symmetry is also assumed. In these initial calculations, we excluded the effect of the atmospheric density decrease with altitude as well as the effect of radiation and ionization, which would decrease the expansion rate of the vapor clouds. Radiation would accelerate cooling, while ionization would absorb a significant amount of internal energy, which is expressed as reduced kinetic energy in the cloud. Thus the effective cross section of our vapor cloud is over estimated, resulting in an underestimate of the downrange travel distance.

The dynamical response of a vapor cloud moving downrange at either 5 km/s or 8 km/s in the dense atmosphere of Venus is similar. First, highly compressed impact vapor expanding against the ambient atmosphere creates a strong shock front (Fig 1a). Because the translational velocity of the vapor, atmospheric response is asymmetric: elongated in the direction of the translational motion with higher pressure at the leading front and lower pressure at the tail (Fig. 1b). As the shock front develops, expansion decreases the density, pressure, and temperature of the inner core, thereby producing a shell-like structure (Fig. 1c). The downrange motion enhances density and pressure at the leading front and results in a hemispherical shell. As this shell travels farther downrange, Rayleigh-Taylor (R-T) instability develops on the leading front and Kelvin-Helmholtz instability is produced on the sides (Fig. 1d). The R-T instability evolves into plumes associated with vortices (Fig. 1e). By this time, temperature in the impact vapor cloud has decreased close to the condensation temperatures for silicate and metals (3,000 - 4,000°K). Due to the absence of radiational cooling, however, this temperature is overestimated here. The downrange motion of the vapor cloud also has stopped by this time with the total downrange travel distance for the center of mass achieving 9 or 23 times of radius of the initial vapor cloud for the cases of 5 km/s or 8 km/s initial downrange velocity, respectively. It should be noted that the 60% increase in initial downrange velocity results in a 155% increase in total travel distance. Presumably this results from dynamic reshaping of a vapor cloud. The shape of shock front in Fig. 1d evolves into an elongate (rather than hemispherical) front, which reduces the effective cross section of the vapor cloud. The reshaping is more pronounced in the higher downrange velocity case and results from greater shock pressure (hence larger propagation velocities) at the leading front. This dynamical reshaping may be similar to the shock collimation effect previously observed experimentally [1, 4].

**Runout Flows around Venus Craters:** Runout flows from craters on Venus occur downrange and appear to be deposited prior to lobate ejecta for sufficiently low-angle impacts as determined by the distribution of ejecta [1]. These observations suggest that the runout flows may have evolved from melt and condensation of impact vapor. The runout flows appear to have a "source region" that becomes more offset from the crater center with decreasing impact angle. The runout flow source region is identified as an area where runout flows change their flow direction from impact-controlled (i.e., downrange) direction to gravity-controlled (i.e., topographic gradient) direction. We use the uprange edge of this central structure (i.e., central peak or central peak ring) as a first-order approximation for the point of maximum energy transfer, which is offset from the geometric center and depends on the impact angle [1, 5]. As impact angle decreases, this region shifts uprange relative to crater center. Downrange offset ($L$) of runout flow source regions is scaled by impactor radius ($r_p$) for comparison with theoretical results. Impactor radii are estimated from scaling relations based on the size of central structures of craters [6]. Although impactor size also can be estimated from scaling relations for the pre-collapsed crater size [7], the scaling relation based on central structure diameters significantly reduces scatter in the data in Fig. 2. Impact angle is estimated from the uprange ejecta missing sector angle [1, 8]. Downrange offset of runout flow source regions has a very strong and clear anti-correlation with impact angle (Fig. 2). This indicates that a larger fraction of the initial momentum of an impactor is inherited by the vapor cloud as impact angle decreases [1]. If we apply our initial results to these observations, $L/r_p$ values of 8-30 for 40° impacts on Venus would correspond to about 5-10 km/s for the initial downrange translational velocity of a vapor cloud.

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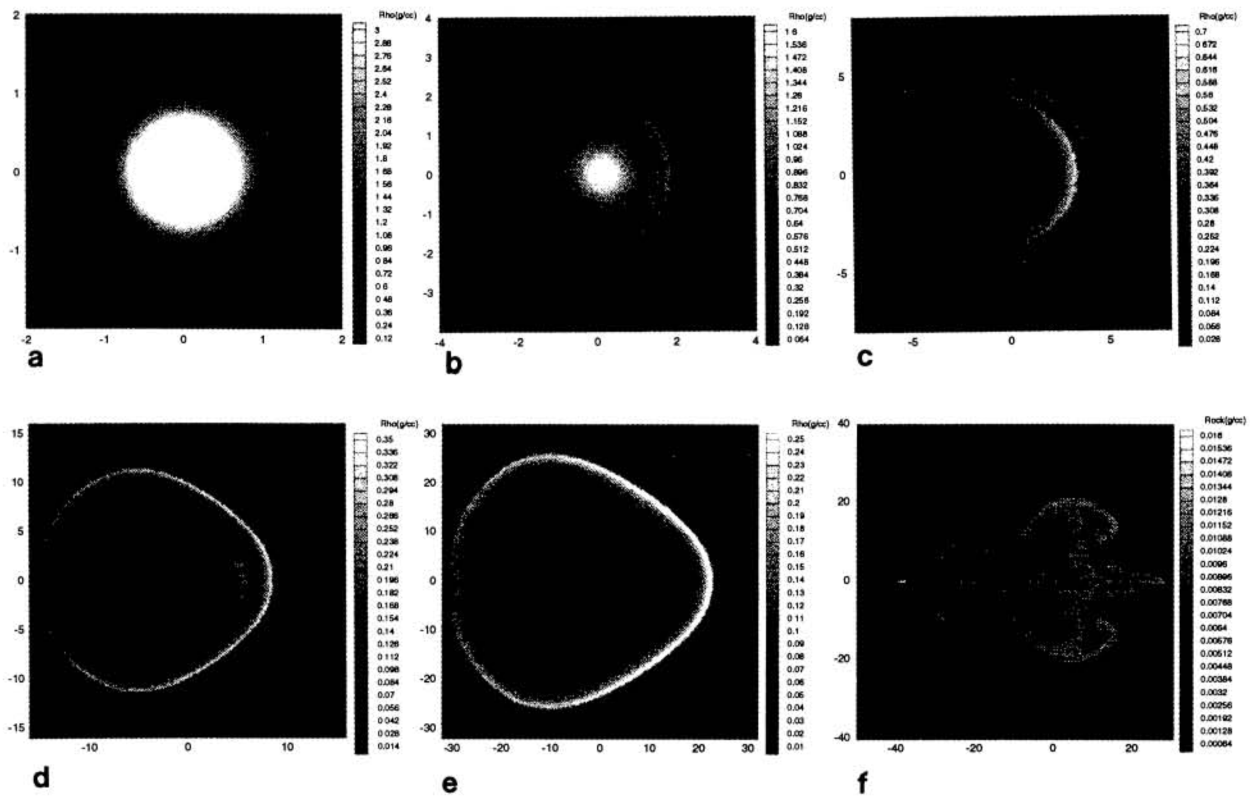
A distinctive morphologic feature of runout flows on Venus is their branching into separate lobes [1]. Although branching far from the runout flow source regions are probably a local topographic effect, some branching develops very close to crater rims and appears to be independent of local topography. Some of the proximal branchings may result from R-T instabilities observed in our theoretical study as well as disruption of the impactor.

**References** [1] Schultz, P.H. (1992) *JGR*, **97**, 16183-16248, [2] Sugita, S and P.H. Schultz (1994) *LPSC abstract* **25** 1355-1356, [3] e.g., Yabe, T. *et al.* (1994) *J. Geomag. Geoelectr.* **46**, 657-662, [4] Schultz, P.H. and S. Sugita (1994) *LPSC abstract* **25** 1215-1216, [5] Schultz, P.H. (1994) *LPSC abstract*, **25**, 1211-1212, [6] Schultz, P.H. and D.E. Gault (1993) *LPSC abstract*, **24**, 1257-1288, [7] Schmidt, R.M. and K.R. Housen (1987) *Int. Impact Eng.* **5**, 543-567, [8] Gault, D.E. and J.A. Wedekind (1978) *Proc. Lunar Planet. Sci. Conf. 9th*, 3843-3875



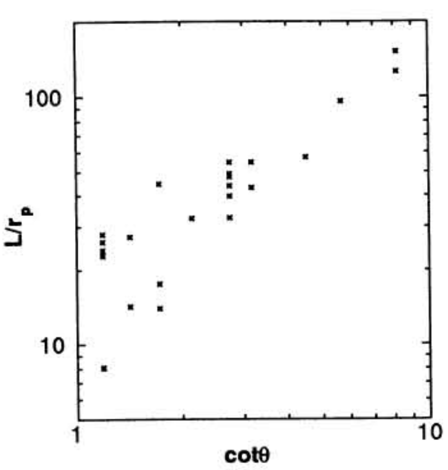




Fig. 1 Time sequence of density distribution of a vapor cloud on Venus. Impact direction is from left to right. The center of mass of impact vapor is fixed at the origin in each diagram. The axis scale is in kilometer. Time after impact and downrange travel distance for each frame are; a) 0.08s, 0.63km, b) 0.28s, 2.2km, c) 0.77s, 5.2km, d) 2.3s, 11.1km, e) 9.9s, 19.8km, f) 44.5s, 23.1km, respectively. The diagram (f) shows density only within the impact vapor cloud.

Fig. 2 Observed downrange offset of the runout flow source region as a function of impact angle, $\theta$, for craters on Venus. The downrange offset, $L$, is scaled by impactor radius, $r_p$, and is measured from the position of the central peak. Such observations allow estimating the initial translational velocity of the vapor cloud through comparisons with theoretical results as discussed in the text.