COMPARISON OF VOLCANIC ASH SETTLING RATES ON EARTH, MARS AND VENUS.

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Introduction: The geologic records of Earth, Mars and Venus all feature evidence that explosive volcanic eruptions injected ash high into the atmosphere. Eruptions on these planets have different gravity and atmospheres with different composition, viscosity, and temperature, pressure, and density profiles. We investigate the influence of these differences on the settling times of volcanic ash particles. Subsequently, with the simplifying assumption of perfect coupling to the lateral motion of the atmosphere, the settling time becomes a surrogate for the distance from the vent.

In the planetary cases, the relationship of deposits to possible source volcanoes remains unclear, which calls into question the plausibility of volcanism as the origin [1]. Some have speculated that highly explosive eruptions from Tharsis volcanoes may have contributed to deposits of the Medusae Fossae Formation (Fig. 1) and the interior of Valles Marineris [e.g., 1,2]. Widespread layered deposits of possible volcanic origin are also found in Arabia Terra, Terra Meridiani, the Hellas and Argyre Basins [3-5]. Reworked and redistributed ash may contribute significantly to some deposits [6,7]. On Venus, possible explosive volcanism has been suggested to explain sharp increases, followed by exponential decay, in SO_2 observed at the cloud tops by Pioneer Venus Orbiter [8] and Venus Express [9]. Although Venus' dense atmosphere inhibits buoyant rise, there are some conditions under which explosive volcanism could transport volcanic ash to significant heights within the atmosphere [10].

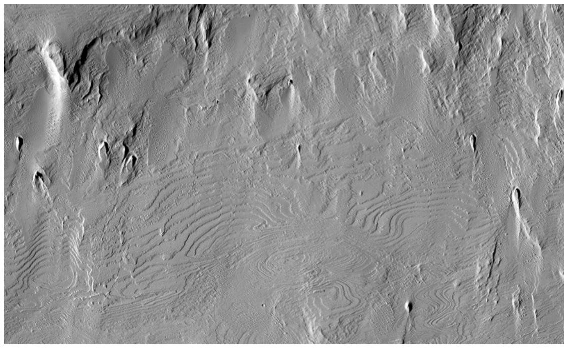

Figure 1. Layered deposits of the Medusae Fossae Formation. Eruptions from the Tharsis volcanoes may have contributed readily-erodable ash to the interior of this formation.

Approach: All particles are transported upward by a buoyant volcanic plume to a specified altitude. Then, the motion is governed by Newton's second law and the appropriate atmospheric and gravitational parameters.

$$m\frac{du}{dt} = mg - \frac{1}{2}C_d\rho_a u^2 A \tag{1}$$

Values of C_d range over three orders of magnitude from ~0.2 for airfoils to extreme values of ~225 for small particles in a low-velocity, low-Re regime [e.g., 10,11], where $Re = \rho_a ud/\mu_a$. In general C_d depends on Re which in turn depends on the velocity, making (1) more complicated than it might appear at first. Particles may go through three different regimes of motion (Fig. 2), delineated by the three different dependences of C_d, on Re.

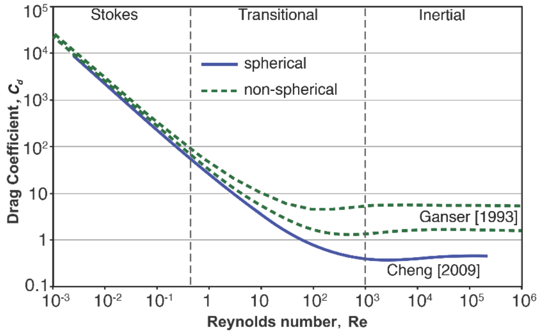

Figure 2. Relationship between Reynolds number, Re, and drag coefficient, C_d, through the Stokes, Transitional and Inertial flow regimes.

Because all particles start with zero velocity in the wind-free case, they must be treated initially by the classical Stokes equation. In general, they would be expected to go into the so-called transitional regime characterized by $1 < Re < 1000$ and a more complicated dependence of C_d, on Re. The settling of particles may even enter the 'inertial regime' ($Re > 1000$) when the atmospheric friction is largely independent of Re.

Results: The influences of gravity and atmospheres of Earth, Mars and Venus have been investigated using the numerical solution of (1) with the appropriate atmospheric density as a function of altitude, atmospheric viscosity, and gravity, for a range of ash particle radii, from 10 μm up to hundreds of microns. For comparison, all particles were started at an altitude of 20 km.

There are dramatic differences in the settling times among the three planets. Velocities ranges from small fractions of a m/s to tens of m/s. While the settling velocity is proportional to gravity, the atmospheric density profile is much more important. The density profiles for each planet are very different from each other and largely control the fall velocities.

The terminal fall velocity increases with increasing particle radius. For each of the atmospheric density considered, there is a critical particle radius for which we expect particles to leave the Stokes regime (Fig. 3). Particle at or below the critical radius reach terminal velocity before the *Re* = 1 limit is attained. Above the critical radius, they leave the Stokes regime without ever reaching the terminal velocity.

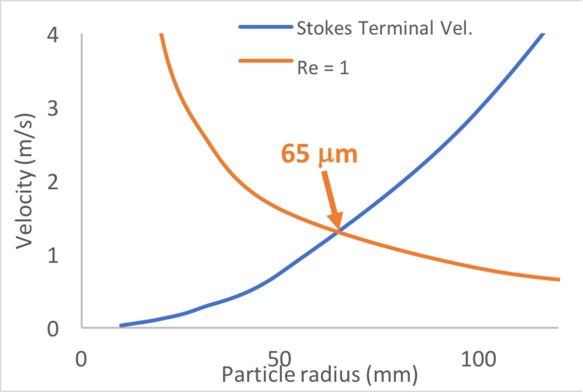

Figure 3. The critical radius is determined by the intersection of the Re = 1 curve (orange) and the terminal velocity equation (blue), both as a function of particle radius. Example show is for the Stokes regime on Earth at 20 km.

The critical radius depends on planetary atmosphere. For Earth, Mars and Venus these critical radii are 65, 310 and 15 μm respectively. Below the critical radii, particles quickly reach terminal velocity and remain there in any fixed atmospheric stratum whose properties can be considered constant. An interesting phenomenon occurs for such particles. Because the atmospheric viscosity for the planets considered is assumed to be roughly constant, particles with radii below the critical values show little change in velocity as higher and higher atmospheric densities are encountered. Thus, they are essentially immune to the atmospheric density changes and continue all the way to the surface at about the terminal velocity with which they started. This is in complete contrast to the particles that exceed the critical radius and move with a velocity that changes significantly with atmospheric density

A particle of any size that starts from a zero downward initial velocity within the Stokes regime will attain terminal velocity and remain at the terminal velocity until it reaches a critical density in the atmosphere. This critical density is found from the Reynolds condition (by assumption *Re* = 1 in our case) and the terminal velocity. Fig. 4 illustrates an example for Mars where the atmospheric density at the surface is the uppermost (orange) horizontal line. The orange line also indicates that critical density for all particles smaller than 143 μm is greater than the atmospheric density at the surface, indicating those particles never leave the Stokes regime. The gray horizontal line indicates that a 300 μm particle will reach critical density at 19 km, and then moves into the transitional regime.

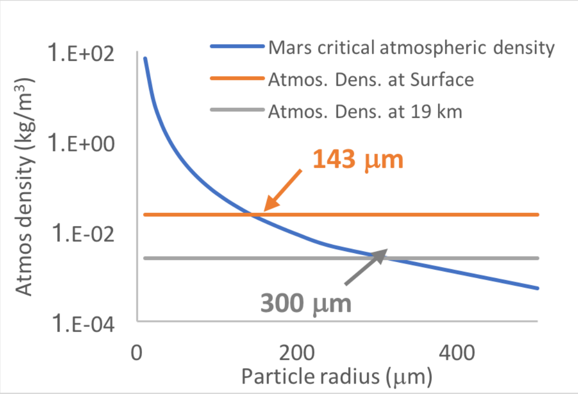

Figure 4 Critical atmospheric density at Mars.

Solving (1), the total time for a 50 μm particle to fall from a height of 20 km through the US Standard Atmosphere is 8.5 hours. A 300 μm particle falling the same distance in the same atmosphere will reach the surface in 39.6 minutes. For simplicity, if one assumes an average horizontal wind component of 20 m/s across all altitudes, these fall times correspond to horizontal transport of 616 km and 47.5 km, respectively.

Conclusions: Understanding how ash particles settle in different gravitational and atmospheric environments is critical to estimating the distances such particles can travel from their source. As particle sizes decrease, their residence time in the atmosphere increases. However, the atmospheric density also plays a critical role in how quickly particles fall. In the thin Mars atmosphere, even larger particles can travel substantial distances. Whereas, within the dense Venus atmosphere, even very small particles fall relatively quickly.

References: [1] Kerber L. et al. (2012) Icarus, 219, 358-381. [2] Hynek B. M. et al. (2003) J. Geophys. Res., 108(E9), 5111. [3] Grant J. A. and Shultz P. H. (1990) Icarus, 84, 166-195. [4] Tanaka K. L. et al. (1992) In Mars, Kieffer H. H. et al. (eds.), Univ. Arizona Press, pp.345-382. [5] Michalski J. R. and Bleacher J. E. (2013) Nature, 502, 47-52, doi: 10.1038/nature12482. [6] Edgett K. S. (1997) Icarus, 130, 96-114. [7] Grant J. A. et al. (2010) Icarus, 205, 53-63, doi: 10.1016/j.icarus.2009.04.009. [8] Esposito L. W. (1981) Adv. in Space Res., 1, 163-166. [9] Marcq E. et al. (2013) Nature Geosci., 6, 25-28, doi:10.1038/ngeo1650. [10] Glaze L.S. (1999) J Geophys Res, 104,18,899-18,906. [11] Clift et al. (1978) *Bubbles, Drops, and Particles*, Academic Press, New York. [12] Seville et al. (1997) *Processing of Particulate Solids*, Blackie Academic & Professional, London, UK.