DISPERSAL OF TEPHRA IN EXPLOSIVE ERUPTIONS ON MARS (2): A QUASI-BALLISTIC MODEL.
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Overview: In a closely related study [1] we derive results for the dispersal of pyroclasts on Mars from relatively steady, long-lived explosive (plinian and sub-plinian) eruptions taking place at low enough mass-fluxes that their eruption clouds are stable in the current martian atmosphere. Here we present a model for pyroclast dispersal from high mass flux plinian/sub-plinian eruptions in which the normal assumptions about eruption cloud-atmosphere interaction do not apply. We show that the same model can be applied to many fire-fountain eruptions on Mars. In both cases we discuss the consequences if the atmospheric pressure were higher in the past.

Background: Early models of convecting volcanic eruption clouds on Mars (see references in [1]) suggested that such clouds should rise much higher than on Earth for a given mass eruption rate. However, [2] showed that many assumptions made in these models about entrainment of atmospheric gases are not justified above about 20 km height on Mars, because of the low density of the atmosphere and the inapplicability of the simple gas laws. Thus eruption clouds from high discharge-rate eruptions, expected to convect to heights much greater than 20 km, cannot do so. This has led us to consider what such eruption "clouds" should look like; we conclude that when entrainment of atmospheric gas is minimal, structures resembling the quasi-ballistic umbrella-shaped plumes on Io [3-5] will form. The rising part of the eruption plume will "punch a hole" through the lower atmosphere, and pyroclasts will only interact with atmospheric gases as they fall back into the denser part of the atmosphere. Here we derive criteria defining the conditions under which a quasi-ballistic modelling approach will be justified. We use the resulting model to predict at what heights and distances from the vent pyroclasts of a given size will be injected from the plumes into the atmosphere, and hence to derive their dispersal distances.

Analysis: A steadily-convecting plinian or sub-plinian erupion cloud is maintained by the buoyancy flux generated by transfer of heat from magmatic gas and pyroclasts to entrained atmospheric gas. The momentum of the magmatic material is shared with entrained gas, and the bulk velocity of the plume rapidly decreases at first, to increase again for a while as buoyancy is generated. Ultimately the cloud slows down, reaches a maximum height, and spreads radially outward and down-wind [6, 7]. For geometric simplicity we treat point-source conduit-type vents rather than fissures; the clouds from fissure vents always approach circular symmetry at great heights above the vent. The rate of atmosphere entrainment is proportional to the upward speed of the cloud on its central axis of symmetry and to the length of the cloud perimeter, and hence the cloud radius. If the atmospheric density is sufficiently small, the total mass flux of atmospheric gas entering the cloud will be a small fraction of the mass flux leaving the vent, no significant modification of the upward momentum occurs, and the rising materials behave ballistically. As they eventually descend, over a wide area, they fall into and mix with a much larger volume of atmosphere, and heat and momentum exchange through drag forces can no longer be neglected, at least in the lower part of the atmosphere where the normal gas laws apply. However, a ballistic treatment of their upward paths is justified.

Figure 1 shows the geometry implied, with clasts launched at speed U_{aM} at an angle θ to the vertical on the path $y = (\cos\theta / \sin\theta)\, x - [g / (2\, U_{aM}^2 \sin^2\theta)]\, x^2$ (1) reaching a maximum height $H = [(U_{aM}^2 \cos^2\theta)/(2 g)]$ (2) at a distance $X = [(U_{aM}^2 \sin 2\theta)/(2\, g)]$ (3) from the vent and then falling back a distance $(H - Z)$ to re-enter the denser part of the atmosphere at height Z above the surface at a radial distance $R = (X + [U_{aM} \sin\theta\, [2(H - Z) / g]^{1/2}])$ (4) from the vent. It is difficult to predict the maximum angle from the vertical at which pyroclasts will be projected upward, but by analogy with the appearance of eruption plumes on Io, we assume $\theta_{Max} = 30°$ to be an upper limit and also give results for $\theta_{Max} = 10°$. Following the arguments of [2] we take Z as 20 km. The values of the eruption speeds, U_{aM}, of gas and small clasts after decompression to martian atmospheric pressure in explosive eruptions are given as a function of the equivalent exsolved magma water content, n, in [1]. These are used in Table 1 to find, for each n, the values of H, X, Y and R for each of $\theta = 10°$ and 30°. Table 1 shows that volatile-rich magmas (those with equivalent water contents in excess of ~1.45 mass % if $\theta_{Max} = 10°$ and ~1.9 mass % if $\theta_{Max} = 30°$) can easily project clasts to heights > 20 km, and thus all require the non-traditional treatment of the dynamics proposed here.

We argued earlier that a quasi-ballistic treatment will also be required for *any* eruption in which the erupted mass flux dominates the entrained atmosphere mass flux. We use the envelope of the outer edge of the rising ejecta given by eq. (1) above and the ballistic equations to find the radius r of the eruption "jet" and the speed U of the pyroclasts as a function of height, and then evaluated the total mass flux of atmosphere being entrained [8] by integrating the local fluxes over all heights, where local flux = ($\sim 0.065\ U\ \pi\ r^2 \times$ atmosphere density). The Mars atmosphere model of [9] is used for the density. This treatment overestimates atmosphere inflow because, if the ballistic model is applicable, pyroclasts falling back through the atmosphere will interfere with radial air inflow [10]. Thus we feel safe in defining the critical lower limit on the erupted mass flux, M_{crit}, at which this model is applicable as the erupted flux at which the atmosphere inflow just equals the erupted flux. Values of M_{crit} are given in Table 1.

Results: Under current Mars atmospheric conditions: 1) Clasts from volatile rich (exsolved equivalent H_2O contents > ~2 mass %) eruptions on Mars will form Io-type plumes and re-enter the dense lower atmosphere at radial distances from the vent of at least several tens of km and possible up to ~100 km. The calculations of dispersal in the current martian atmosphere given in Table 5 of [1] show that coarse (several mm-sized) pyroclasts will be transported for an additional 10-20 km downwind while fine (tens of microns) particles can travel for at least many thousands of km. 2) If the range of mass fluxes in basaltic eruptions on Mars is similar to that on Earth, up to 0.5 to 1 $\times 10^6$ kg/s, then the values of M_{crit} given in Table 1 imply that all such eruptions with exsolved equivalent H_2O contents up to ~0.4 mass % will behave in accordance with the quasi-ballistic model developed here, significantly simplifying the analysis of their deposits. The model will apply to higher mass flux eruptions over an even wider volatile content range.

We note that both of these results depend critically on the current low martian atmospheric pressure. A pressure increase by a factor of ~10 would suffice to force fire-fountain eruptions to more closely resemble those on Earth and an increase by a factor of ~30-100 would do the same to plinian/sub-plinian eruptions

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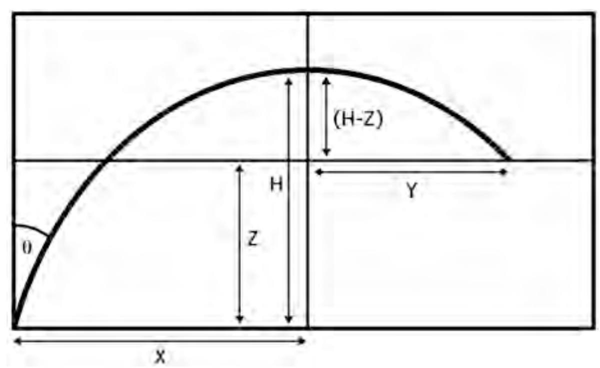

Figure 1. Geometry of quasi-ballistic model.

Table 1: Parameters of quasi-ballistic eruption plumes (see Fig. 1) on Mars. Parameters are defined in the text. A blank entry means that the ~20 km height where the gas laws break down is not reached.

		values for θ_{Max} = 10°					values for θ_{Max} = 30°				
n mass %	U_{aM} (m s^{-1})	M_{crit} kg/s	H km	X km	Y km	R km	M_{crit} kg/s	H km	X km	Y km	R km
0.1	95	3.0×10^4	1.2	0.4			3.6×10^4	0.9	1.1		
0.3	176	6.0×10^5	4.0	1.4			1.2×10^6	3.1	3.6		
0.5	234	2.2×10^6	7.1	2.5			4.8×10^6	5.5	6.4		
1.0	340	1.0×10^7	15.1	5.3			2.4×10^7	11.7	13.5		
1.5	421	2.3×10^7	23.1	8.2	2.99	11.13	5.5×10^7	17.9	20.6		
2.0	488	3.2×10^7	31.0	11.0	6.53	17.48	8.5×10^7	24.0	27.7	11.3	39.0
3.5	642	4.6×10^7	53.7	19.0	15.01	33.96	1.3×10^8	41.5	48.0	34.6	82.5
5.0	756	5.6×10^7	74.5	26.3	22.47	48.75	1.6×10^8	57.6	66.5	53.8	120.3