Lightning and Ice in Volcano Clouds

Arthur A Few, Professor Emeritus
Physics and Astronomy, Rice University
700 Hill St; Gold Hill
Boulder, CO 80302-8786
few@rice.edu
http://www.ruf.rice.edu/~few
http://www.afewatm.com/

The Eyjafjallajökull volcano in southern Iceland. Photo on 2010 April 17
Credit & Copyright: Marco Fulle. Permission from Marco Fulle - www.stromboli.net

The photograph above is beautiful and also informative. In it we see both kinds of electrical discharges produced by volcanos: discharges produced near the vent and discharges emerging from the volcanic cloud higher in the plume. The upper discharges look exactly like negative cloud-to-ground lightning from thunderstorms. If this is the case then the lower plume near the terminus of the bright lightning channel would be charged positively. Many of the lower branches of this lightning flash are also moving toward the lower plume.

Alaska's Redoubt Volcano March 2009, Photo by Bretwood Higman

The discharges in the lower plume appear quite different. They are short and reddish in color; the plume has a very large optical thickness, so we only see the portions of the discharges that are close to the edge or may exit the plume for a short distance. The reddish emission extends beyond the discharge channel indicating that the discharge is heating the surrounding ash, which then radiates the reddish radiation.

Plinian Volcanos

Plinian and Ultra Plinian volcanos are the most explosive types of volcanoes.

1. Plume heights typically exceed 25 km, some as high as 40 km.[2]
2. The explosive expansion is produced by exsolution of volatiles. One m^3 of magma expands to ~670 m^3 when the volatiles are released at 1 atm. See Figure 1 below.[2]
3. The magma is rhyolitic and contains mostly silicates.
4. Water is the dominant volatile; as much as 99% molar fraction[1], and up to 7% by mass in the molten magma.[2]
5. Other volatiles are CO_2 and compounds of S, Cl, and Fl, which form gases as the magma pressure decreases.[2]
6. Plinian plumes inevitably contain ice because of the height of the plume and the abundance of water. Other volcanic plumes topping out lower than the Plinian may also contain ice.

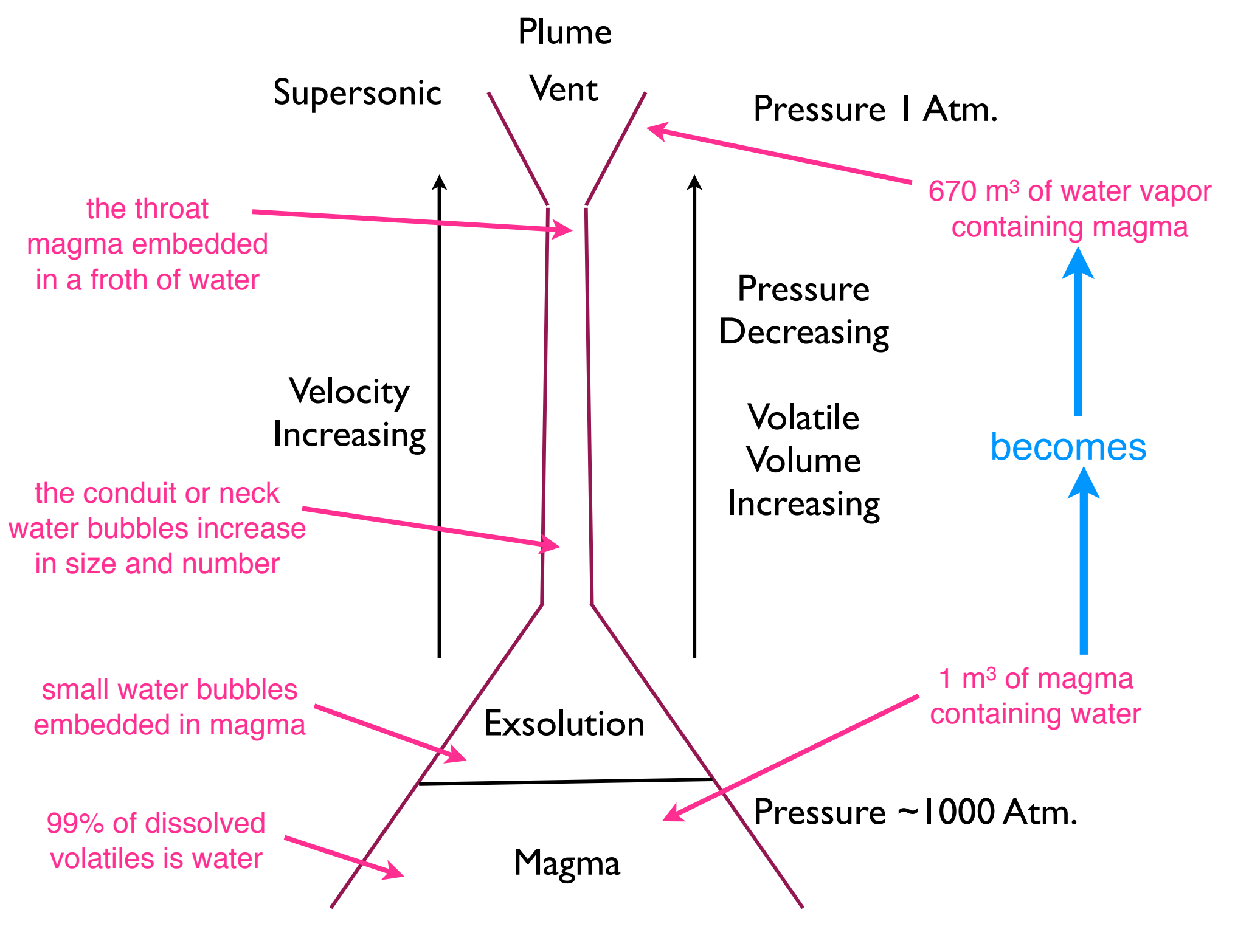


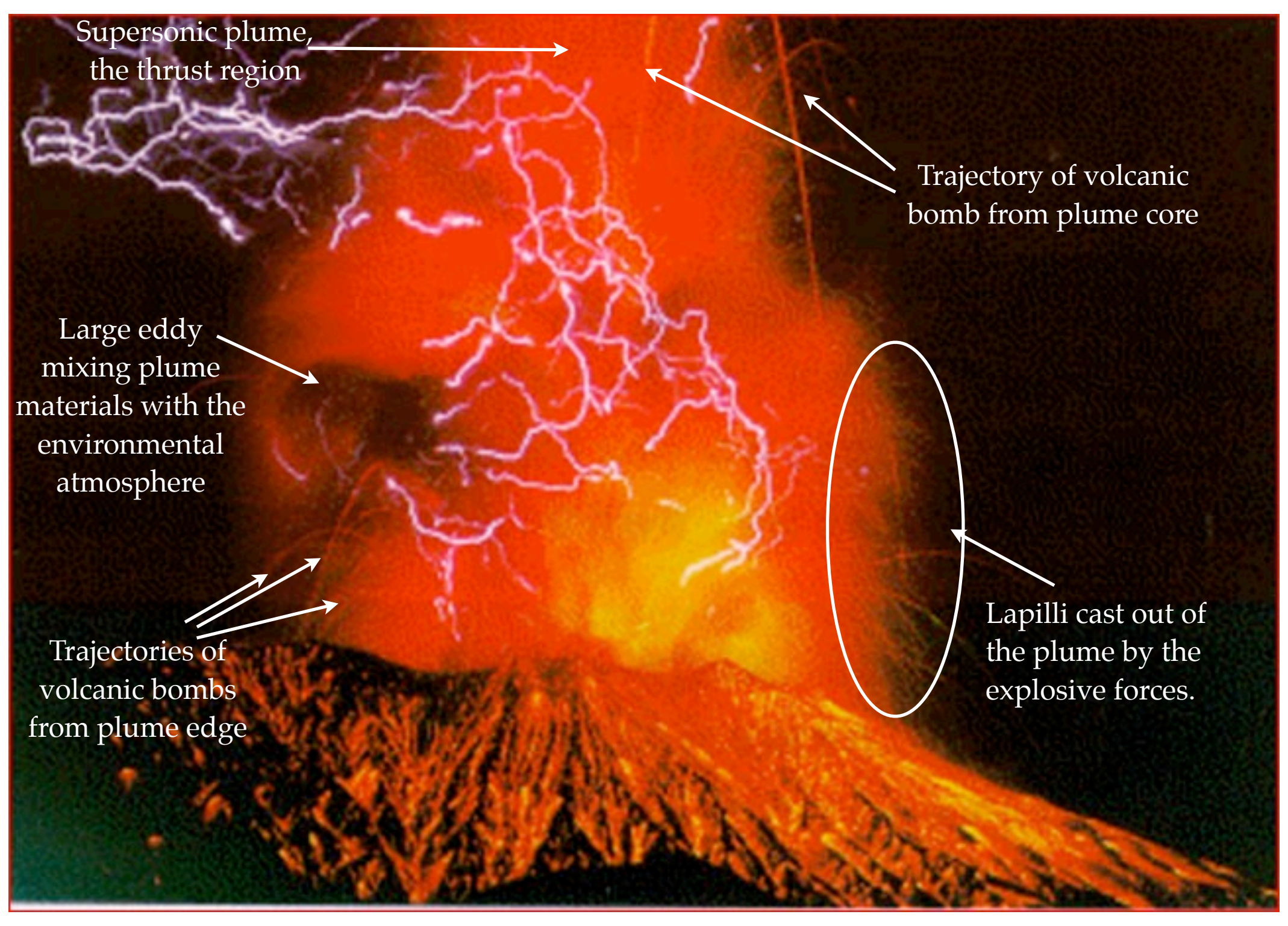
Figure 1
Drawing above is based upon Sparks *et al.*[2]

See the drawing, Figure 1 above; the following discussion is based upon Sparks *et al.*[2] The conditions in the magma chamber at depths 3 km to 30 km below the surface are, for rhyolite magmas, ~ 900 °C and ~ 1000 atm. The central components of Figure 1 (black and purple) depict the structure and dynamic events during a Plinian eruption.

Along the left side in red from bottom to top, we track the changes in the water component as it moves upward in the conduit or neck. Small water bubbles appear in the exsolution region; this expands the volume of the magma forcing the upward motion of the magma. Moving upward in the neck pressure is decreasing; the number and size of the bubbles is increasing and the upward velocity is increasing. Thus far the water component and the magma melt remain in thermodynamic equilibrium. Upon reaching the throat just below the vent the bubbles have become the predominant dynamic component of the magma. Rather than a magma containing bubbles, we now have a "froth"of bubbles containing magma melt. In the vent at 1 atm. the bubbles undergo a rapid expansion producing a upward focused explosion. The gas and magma separate dynamically and thermodynamically; the magma with its mass and heat capacity maintains a temperature ~ 700 °C - 750 °C, while the explosive expansion rapidly cools the gas as it moves upward supersonically. The expansion can cool the gas component to ~ 400 °C. The larger tephra fall out of the plume rapidly while the smallest lapilli and ash move with the plume gas and come into thermodynamic equilibrium probably somewhat above 400 °C.

Along the right side of the figure in red and blue is a summary of the net changes in the magma during the passage from the magma chamber at ~1000 atm. and the surface at 1 atm. The volume changes from 1 m^3 at depth to 670 m^3 at the surface.

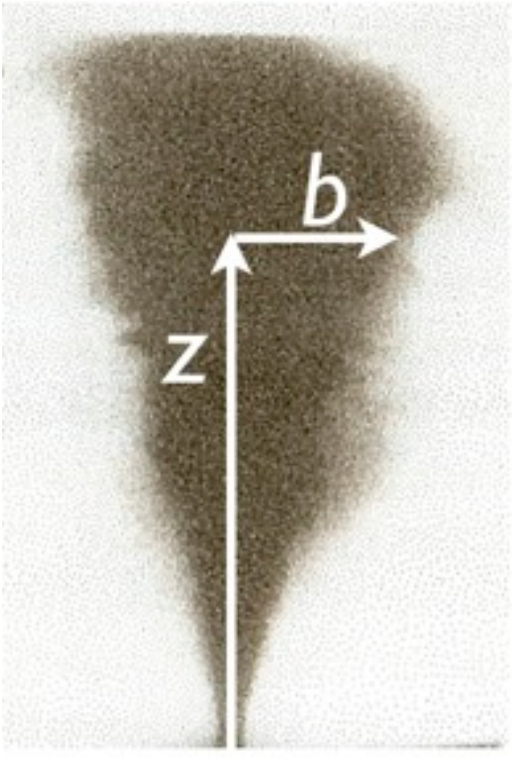
Sakurajima Volcanic Lightning; May 18,1991



Sakurajima Volcanological Observatory

Several important processes are evident in the above photograph. Just above the vent the explosive force of the expanding gas is forcing the lapilli out of the plume. That horizontal force with the addition of gravity is removing the larger components including volcanic bombs. The effluent from the vent (yellow) is hotter than the other parts of the plume (red). The core of the plume seen at the top of the photograph is moving upward very fast; this is the region of plume thrust where the upward velocity is a remanent of the focused explosive forces in the upper conduit and vent. A large eddy is evident lower left illustrating the importance of entrainment in modifying the plume. Finally, the emission in this night photo indicates that radiative cooling is another source of plume cooling.

Cooling and Slowing the Plume



During the thrust phase of the plume the boundary is very turbulent and the behavior can be approximated by that of jet flow, figure left; based upon experimental data[2], $b = z/8$. The turbulent flow at the edge produces mixing of the ambient air with the plume, which decelerates and cools the plume. Using this simple jet flow model with a vent radius equal 20 m, the radius of the jet will be approximately 125 m at 1 km above the vent. Assuming a vent radius of 20 m we estimate the momentum in a column in the core of the jet. By the entrainment mechanism this momentum is distributed throughout the entrainment cone; at 1 km above the vent the velocity of the expanded jet will be approximately 31 m/s, which is near the updraft velocity of an active thunderstorm. We estimate the heat content in the core of the jet from the estimated temperature of 400 °C and the heat content of the entrained air from an assumed temperature of 10 °C; these are mixed and the total heat content is distributed over the entrainment cone giving us a temperature of 62 °C at 1 km. Admittedly, one has a lot of latitude in selecting values for the parameters used in these estimates, but it is evident that entrainment greatly reduces the velocity and temperature of the plume within a kilometer or so of the vent. The temperature remains very warm compared to the ambient air. The high-speed jet flow, which was produced by the thrust of the explosive volcano, is replaced by buoyant plume dynamics above the thrust region; modified cloud models can be used to describe subsequent development. The plume continues its upward motion propelled now by its primitive heat. Entrainment continues to be a major source of cooling; simple models indicate that entrainment is proportional the upward velocity of the center of the plume[5]; adiabatic expansion and radiation also adds to the cooling. The plume is rising through a ambient atmosphere which is also cooling steadily with altitude, so the buoyancy remains the driving mechanism for most of the plume evolution. The reason that some Plinian plumes can reach heights of 25 km to 45 km, penetrating into the lower stratosphere, is that their temperatures never fall below the ambient atmosphere temperatures.

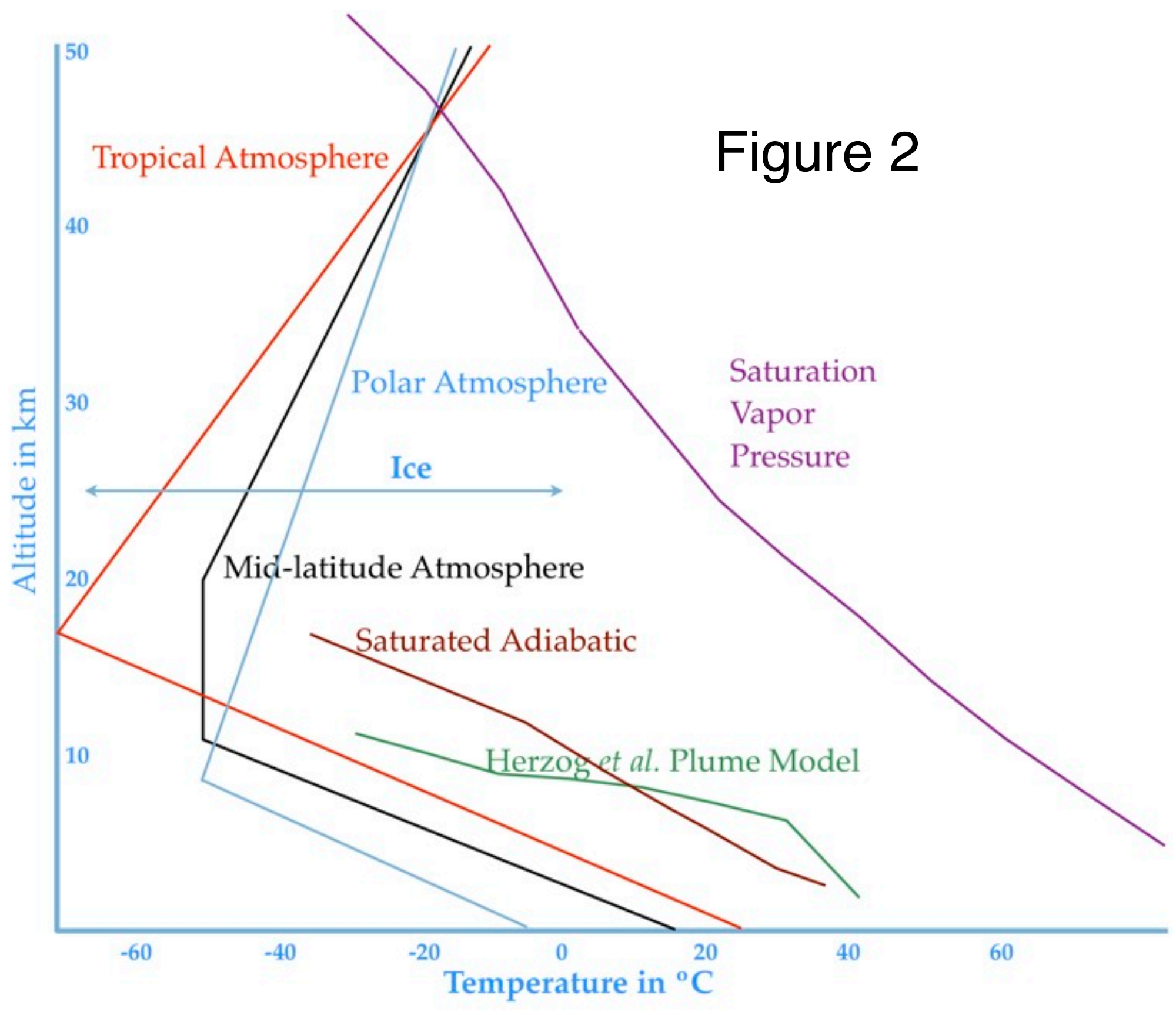


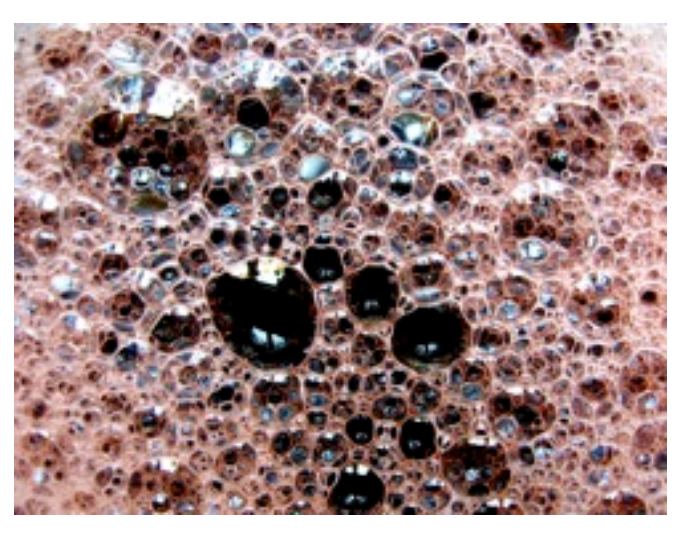
Figure 2

Several curves are plotted in Figure 2 above on linear Altitude versus Temperature diagram. On the left side are schematic representations of the environmental profiles for tropical, mid-latitude and polar atmospheres. As long as a volcanic plume/cloud remains to the right of the appropriate profile it will remain buoyant. The "Saturated Adiabatic" curve is an extension of the conditions computed above for the top of the thrust region of the jet from the vent; a thermodynamic diagram was used to plot this curve. The curve labeled "Herzog *et al.* Plume Model" is derived from their Figure 5.[6] Their model is a cloud physics model including microphysics that is placed in a moist tropical environment. Among their conclusions are the significance of moisture entrainment and latent heat releases to the cloud evolution. Finally, the right-most curve "Saturated Vapor Pressure" was computed using the Clausius-Clapeyron equation. This curve represents the upper boundary for clouds because it assumes that the vapor is providing the total pressure in the cloud.

The horizontal line labeled "Ice" is the temperature region where ice can exist; although, ice formation is usually initiated around -10 °C to -20 °C. This diagram indicates that most if not all volcanic clouds should produce ice above 10 to 15 km.

Production of Magma Fragments

In the volcano throat in Figure 1, we have this froth of water vapor bubbles individually surrounded by a thin layer of the magma melt. During the rapid expansion of the bubbles in the vent the thin magma melt is shattered into fragments, which may produce charging. These fragments subsequently become ash (< 2 mm), lapilli (2 mm<> 64 mm) and ice nuclei (< 1 mm). We can get an estimate of the range of sizes of these fragments with a rather simple model. Starting with the assumption that we have 670 m^3 of bubbles and 1 m^3 of magma melt, we distribute the magma in a layer around the spherical bubbles. If there is a single bubble the thickness of the surface layer would be ~3 mm. However, if there are 10^3 small bubbles the magma layer thickness would be ~ 0.3 mm. Obviously the bubbles will not all be the same size. The froth photo left is red wine with a drop of dish soap to stabilize the bubbles for photographing. The arrangement of touching circles in two dimensions is called Apollonian Gaskets[7]; there is a mathematical relationship among all of the circles.



Ice Nuclei in Volcanic Clouds and Overseeding

Durant et al.[4] is an authoritative resource for ice nuclei and the associated physics of nucleation. "In the context of explosive eruptions where super-micron" (1 - 1000 μm) "particles are plentiful, this result implies that volcanic clouds are IN-rich relative to meteorological clouds, which typically are IN-limited, and therefore should exhibit distinct microphysics."

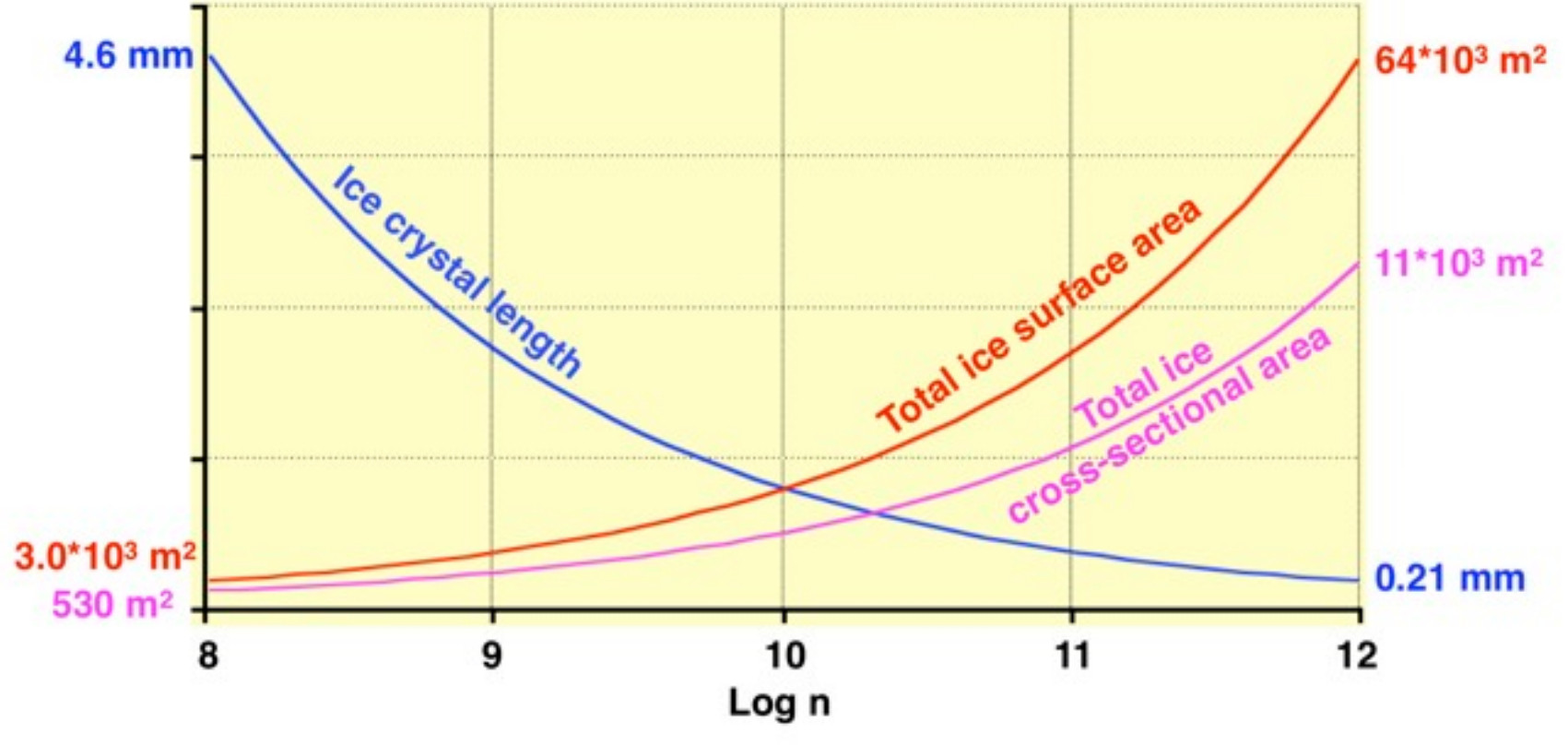


Figure 3

The curves in Figure 3 above are useful to understanding the consequences of the overseeding of ice in volcanic clouds.[4] In summary, ice nuclei are sparse in thunderstorm clouds; hence, there are few ice particles but they can grow large on the available vapor. In contrast volcanic clouds contain numerous ice nuclei particularly silicates, and they can develop as many small ice particles, which can deplete the available water vapor supply. This great difference in ice behavior between the thunderstorm clouds and the volcanic clouds can have significant impact on electrification, cloud evolution and chemical transport into the stratosphere.

To produce Figure 3, I took 1 m^3 of water and distributed it into "n" hexagonal rod crystals each having a side dimension "a" and length "5a". I then computed for each value of n the total surface area and cross-sectional of the whole collection of crystals. The results are displayed in the figure. We easily see that increasing the number of crystals, increases the total surface and the cross-sectional areas of the system.

1. Electric charge resides on the surface of ice particles; hence, the more numerous but smaller ice particles have a greater electrical capacity.

2. The adsorption capability of ice particles for chemicals in the volcanic plumes is also proportional to total surface area.

3. The smaller ice particles are more easily lofted into the stratosphere transporting the volcanic chemicals.

4. Ice-ice contact is a source of electrical charging and the frequency of particle collisions is increased with increased total cross-sectional area.

Redoubt Volcano, Alaska – Alaska Volcano Observatory
Photograph by R. Clucas April 21, 1990, U. S. Geological Survey

This photograph was taken during calm winds and reveals the vertical structure of the volcanic cloud. The vigorous cloud penetrates through a couple of thin stable layers then enters the stratosphere transporting large quantities of ash and volcanic chemicals.

Something New - Green Lightning

Chalten, Chili, 2008

Green lightning! I've not seen this before. My guess is that this discharge originated as a negative downward discharge that entered the plume and did not terminate with a return stroke. The channel retained its negative charge and produced a corona current around the channel; this excited oxygen atoms that returned to ground state to emit green light much like an aurora.

Summary

- Electrical discharges involving the upper regions of the volcanic clouds appear in all aspects to be identical to thunderstorm lightning. Ice is most likely present and ice-ice contact is the likely charging mechanism.
- Electrical discharges in the lower regions of the plume are different and are likely the result of contact charging between molten magma and somewhat cooler vent materials and also the fracturing of magma[8].
- The plume is optically thick and modifies the visual characteristics of discharges usually obscuring them completely.
- All Plinian volcanos will produce lightning owing to their height and water content. Other tall volcanos may also produce lightning.
- Following the focused explosion at the vent, initial cooling occurs by: (1) rapid expansion of the gaseous components, (2) fall out and expulsion of the heaver and hotter magma components, and (3) radiative cooling.
- The next stage of plume development is the thrust region in which the upward velocity is the remnant momentum from the focused explosion. In this stage the plume is slowed and cooled by entrainment of environmental air.
- Above the thrust region the buoyancy of the plume becomes the driving force maintaining its upward motion. This buoyancy dynamic is essentially the same as in clouds, and cloud models adjusted for plume conditions can be used for the volcanic clouds. Cooling continues by expansion, entrainment, and radiation.
- Sufficient cooling will occur in tall plumes (> 10 km) for ice to form and ice-related electrical charging leading to lightning.
- Ice crystals in Volcanic clouds are smaller and more numerous than those in thunderstorms. This can lead to more vigorous charging and enhanced transport of chemicals into the stratosphere.

Acknowledgment

This research received support from the Charles L Conly Endowment Research Fund

References

1. Symonds, R. B., W. I. Rose, G. J. S. Bluth, and T. M. Gerlach (1994), Volcanic gas studies - Methods, results, and applications, in *Volatiles in Magmas*, pp. 1-66, Mineralogical Society of America, Washington, D. C.
2. Sparks, R. S. J., M. I. Bursik, S. N. Carey, J. S. Gilbert, L. S. Glaze, H. Sigurdsson, and A. W. Woods (1997), *Volcanic Plumes*, 574 pp., John Wiley, Chichester, U. K.
3. Jakosky, B. M., 28(1986), Volcanoes, the Stratosphere, and Climate, pp.247-255, *J. Volcanology and Geothermal Research*, Elsevier Science Publishers B. V. Amsterdam.
4. Durant, A. J., R. A. Shaw, W. I. Rose, Y.MI, and G. G. J. Ernst (2008), Ice nucleation and overseeding of ice in volcanic clouds, *J. Geophysical. Res.*, **113**. D09206, doi:10.1029/2007JD009064.
5. Morton, B.R., Geoffrey Taylor, and J. S. Turner (1956), Turbulent Gravitational Convection from Maintained and Instantaneous Sources, pp. 1-23, *Proc. R. Soc. Lond. A*, **234**, doi: 10.1098/rsps.1956.0011.
6. Herzog, Michael, Hans-F. Graf, Christiane Textor, Josef M. Oberhuber (1998), The effect of phase changes of water on the development of volcanic plumes, pp. 55-74, *Journal of Volcanology and Geothermal Research*, **87**, Elsevier Science B.V.
7. Mackenzie, Dana, A Tiskit, a Taskit, an Apollonian Gasket(2010), pp. 10 -14. *American Scientist*, Volume **98** Number 1.
8. Behnke, S.A., R.J. Thomas, P.R. Krehbiel, and S.R. McNutt (2012), Spectacular Lightning Revealed in 2009 Mount Redoubt Eruption, pp.193-194, *EOS, Transactions, American Geophysical Union*, **93**, Number 20.