An approach to *In-situ* observations of volcanic plumes.

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Introduction: Volcanoes have long been recognized as playing a dominant role in the birth, and possibly the death, of biological populations. They are possible sources of primordial gases, provide conditions sufficient for creating amino acids, strongly affect the heat balance in the atmosphere, and have been shown to sustain life (in oceanic vents.) Eruptions can have profound effects on local flora and fauna, and for very large eruptions, may alter global weather patterns and cause entire species to fail. Measurements of particulates, gases, and dynamics within a volcanic plume are critical to understanding both *how volcanoes work* and *how plumes affect populations, environment, and aviation*. Volcanic plumes and associated eruption columns are a miasma of toxic gases, corrosive condensates, and abrasive particulates that makes them hazardous to nearby populations and poses a significant risk to all forms of aviation. Plumes also provide a mechanism for sampling the volcanic interior, which, for hydrothermal environments, may host unique biological populations.

Measurements of the interior of plumes are historically sparse because the small extinction pathlength thwarts attempts at remote sensing, and because the risks of flying fixed-wing aircraft through an abrasive particulate environment has prevented accurate *in situ* sampling. An aerobot provides an excellent platform for sampling plumes due to its inherent buoyancy, station-keeping capability, heavy lift capacity, and remote operability. An aerobot is also ideal for deploying a tethered platform for exploring vertical profiles and for measurements in environments too challenging for airplane-based platforms.

Applications of plume measurements: Plumes provide a window into understanding how volcanoes work and measuring the composition and evolution of the underlying magma and serve as harbingers of significant volcanic activity. Measurements of volcanic plumes can lead to advances in understanding where we came from, how volcanoes affect us, and mitigation of some volcanic hazards.

Potential Impact on Understanding of Evolution: The study of volcanic plumes can significantly impact our understanding of both environmental and evolutionary processes on Earth. As has been demonstrated by the Pinatubo eruption, [1] the prodigious amounts of dust and reactive gases injected into the stratosphere by large volcanic eruptions can result in significant alterations of the Earth's surface temperature and atmospheric composition. These modifications – particularly to the stratospheric column abundances of highly-reflective sulfuric acid particulates that can produce multi-year temperature changes at the Earth's surface – may, in the extreme, be responsible for mass extinctions, including the death of the dinosaurs. Knowledge of volcanic emissions have played a significant role in alternative hypotheses for mass extinctions – particularly in the analysis of the environmental impact caused by the collision of an asteroid or comet into sulfate-laden rock at Chicxulub [2]Sulfates released into the atmosphere by volcanic plumes can generate sulfuric acid clouds in the stratosphere through reactions involving ultra-violet light and water vapor [2]. As has been demonstrated by Pope et al. [2], these highly reflective aerosols can exist for significant periods of time in the stratosphere, noticeably lowering the Earth's surface temperature. Thus, the study of volcanic emissions and their effects on Earth's climate and environment can have significant impact on our understanding of the evolution of life on Earth.*The Search for Cloud-Based Extremophiles:* Life has been found to exist in a variety of extreme environments, including within the clouds of Earth, as well as near volcanic vents on land and in the deep ocean. Hardy thermophiles such as S. solfataricus [3] survive at near-boiling temperatures (some hydrothermophiles reported survive up to 110^{o} C) and may well thrive in the humid environment near volcanic vents. They may, in turn, be carried aloft on plume particulates. These particulates can be directly sampled from an aerobot, returning the samples to ground-based laboratories for biological analysis

Plume Aviation Hazards: Plumes present a major regional hazard to international aviation [4]and can result in significant local air pollution. Identification of volcanic plumes by remote sensing from satellites is hindered by a lack of effective detection algorithms, lack of good *in-situ* data for algorithm validation, and the limited choice of bands on operational meteorological satellites. This often results in meteorological (e.g., water vapor or ice) clouds being mistaken for plumes and vice versa [5]

The solution to the ash detection problem has several aspects, including understanding volcanic eruption source conditions, implementing good plume dispersion predictive models, understanding the physicochemical interactions of volcanic eruption products with the ambient atmospheric environment, and understanding and predicting the range of spectral characteristics of eruption plumes as they move and evolve within the atmosphere. As many of the plume detection, tracking, and prediction strategies have as their core the "split window" technique outlined above, focusing on the spectral signature of the plume as a basic data set, it is imperative that inferences of plume physical and chemical properties gleaned from airborne and orbital remote sensing data be validated by in-situ measurements of gas and particulate properties. To date this has been accomplished only sporadically and serendipitously [6].

Thus, the most fundamental to the improvement of our ability to detect, track and understand volcanic eruption plume properties will come from in-***situ sampling and measurements of atmospheric conditions within volcanic plumes.*** Aerobot-based observations will provide an important set of boundary conditions for the validation of radiative transfer models of volcanic eruption plumes and clouds, for the validation of 2D and 3D physico-chemical models of volcanic plume dispersion at the meso-scale, and for understanding the relationship between the spectral character of plumes and their physical and chemical properties.

Measurements from Aerobots: Volcanic plumes can profoundly affect our lives. Effects include changing the color of the sunset, damaging aircraft, causing local disasters and, in some cases, altering the chemistry and weather of the entire planet. The exteriors of plumes have been studied extensively, but little has been measured on the physics, chemistry and temporal evolution of the interior of plumes. This is in large part due to the difficulty of viewing the interior of plumes from the outside, and the challenges frequently associated with volcanoes including rough terrain, downslope winds, bombs, gases, and thermal output.Many high priority science objectives can be fulfilled only through obtaining unique measurements of plume interiors. These include 1) providing correlation of *in-situ* observations with the classic remotely sensed measurements obtained from earth and spacecraft based imagers and spectrometers to better relate those measurements to conditions within the plume; 2) determining the plume extent and density (some plume boundary regions, though difficult to detect, still present significant hazards to aviation [e.g., Pieri, et al., 2002]) 3) determining the turbulence, weather, and energy transport within the plume; 4) determining gas and particulate distribution, composition, and temporal evolution to provide new constraints for numerical models of how plumes evolve; 5) measuring the extent (and determining the cause) of the separation of the gas and particulate plumes; 6) determining the change in plume characteristics for a change in source; 7) measuring the rate precipitation and species conversion within the plume; 8) determining the conditions necessary for plume components to exit the troposphere; and 9) using plume particulates to sample the volcano's deep interior and to search for evidence of biological activity within that interior.

In-situ measurements supporting these objectives can be obtained from a aerobot – essentially a commercially available remotely operated blimp modified to have sufficient autonomy to support long duration measurements of temporal variations in plume, to enhance the ability to perform station keeping or to track features of interest, and to support the ability for operations beyond visual contact of the ground crew.

Aerobot design issues: A plume aerobot would consist of a powered blimp and a tethered instrument platform lowered from the aerobot, which hovers above the plume. The platform should be designed for rapid reconfiguration to enable use of multiple instrumentation sets in a single field campaign.

Aerobots allow for relatively low-cost field campaigns. An aerobot provides the capability to sample large thermal areas including fumaroles and calderas – areas that are often inaccessible, but which can have profound effects on the environment through boundary layer interactions. The craft provides an excellent platform for temporal monitoring of flow field evolution. The field aerobot provides many experimental advantages including substantial payload mass and power capability (~100kg, 3kw), excellent range and heavy weather characteristics (~35 kt speed), and the ability to remain on station for long periods of time (~24 hours).

Previous studies indicate that an aerobot is an ideal vehicle for exploring the surface and lower troposphere of Titan for extended periods. The same qualities that make aerobots well suited to *in situ* Titan exploration also make them well suited for *in situ* observations of volcanic plumes at Earth.

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