



Detecting volcanic ash of eruption plumes on Venus by imaging in the near infrared windows

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Volcanic outgassing shapes the evolution of the atmospheres of terrestrial planets, but is itself affected by the atmospheric pressure (Head and Wilson 1986, Phillips et al. 2001, Gaillard and Scaillet 2014). Outgassing can take place in form of explosive eruptions where the exsolution of volatiles from ascending magma accelerates the ascent and drives further exsolution. Observations by Pioneer Venus and Venus Express show that the abundance of SO₂ above the cloud layer (>70 km) varies by two to three orders of magnitude on timescales ranging from weeks to decades and one of the hypotheses brought forward is that explosive eruption plumes cause enhanced mixing between the SO₂-rich (>100 ppm) lower atmosphere below the clouds, and the SO₂-poor (<1 ppm) upper atmosphere above the clouds. (Esposito 1988, Marcq et al. 2013). Models of eruption plumes however show that only very intense eruptions originating at relative high elevations can reach this height (Glaze 1999). On Earth, eruptions of this intensity are rare, lower volume rate eruptions are more frequent. Plume height scales with volume rate (e.g. Glaze 1998, Airey et al. 2015). Thus there is a high probability that there are significantly more plumes that do not reach the cloud layer. Even if the SO₂ variation has a non-volcanic origin, there is evidence suggesting explosive eruptions in form of diffuse deposits that are interpreted as being formed by pyroclastic flows from collapsing volcanic ash plumes (e.g. Campbell et al. 2017). A re-analysis of Venera 13 descent spectroscopic measurements suggests the presence of particles that could be volcanic ash at altitudes around 4 km (Kulkarni et al. 2025).

The frequency of such explosive eruptions is of high scientific interest. The atmospheric pressure suppresses exsolution so that the transition from an effusive to an explosive eruption requires a combination of high eruption rates and high abundance of magmatic volatiles, most importantly H₂O (Airey et al. 2015). The volatile content of Venusian magmas and outgassing efficiency is important for understanding the evolution of the atmosphere (Gaillard et al. 2014). The search for locally enhanced H₂O abundance is an objective of near-infrared imaging of atmospheric windows by upcoming missions to Venus (e.g. Wilson et al. 2024). The H₂O abundance is derived from increased extinction of thermal emission at wavelength of H₂O absorption lines relative to wavelengths with no sensitivity to H₂O (e.g. Bézard et al. 2009), thus requires at least two spectral bands.

The ash entrained in a volcanic plume is however also a significant source of extinction that can reach a large areal extent. On Venus the surface and atmospheric thermal emission radiance in near infrared window regions is sufficiently bright to be measurable through the cloud layer with optical thicknesses on the order of 20-40, however this is due to the very high single scattering albedo of cloud droplets allowing multiple scattering without significant absorptions. The single scattering albedo of volcanic ash particles is lower, resulting in a strong reduction of diffusely transmitted

radiance. In large (Plinian) eruption plumes the hot ash gas mixture buoyantly rises until it reaches near ambient temperature, at which the finer ash particles spread out laterally, forming a so-called umbrella layer. The umbrella regions of eruption plume can be hundreds of km in diameter (e.g. Gupta et al. 2022) which is large compared to the blurring effect caused by multiple scattering of thermal infrared radiation within the clouds (~ 90 km) (Hashimoto and Imamura 2001).

We model the effect of a Plinian eruption plume umbrella layer on radiance observed in the near infrared window regions using the NEMESIS radiative transfer code (Irwin et al. 2008), in order to understand under which conditions a plume would be clearly visible. This is done by introducing various amounts of ash particles with optical properties from Deguine et al. (2020) at various altitudes between the surface and cloud layer. We assume that the particles at the outside of the plume quickly equilibrate with the environment and are thus at ambient temperature. This is supported by Earth remote sensing observations of exceedingly cold brightness temperatures at the top of eruption plume umbrella layers at high altitudes (e.g. Gupta et al. 2022). If the ash layer is sufficiently opaque and at sufficiently higher altitude than the source region of the background emission there is a reduction in top of atmosphere radiance that exceeds the modulation that can be introduced by Venus cloud opacity variations.

Under these conditions a plume can be clearly distinguished in images at just a single wavelength. This would allow imagers with a spectral filter such as Venus Express VMC, Akatsuki IR1, or Parker Solar Probe WISPR to detect such a plume while water vapor abundance measurements have so far mostly been proposed for multispectral or hyperspectral instruments. With a sufficient imaging frequency, even plumes signatures that do not exceed the typical modulation by clouds could be distinguished via their lower zonal velocity.

The above existing and planned Envision and VERITAS datasets could detect eruption plumes but do not represent a very extensive monitoring capability due to the limited frequency and areal coverage of imaging. However, there are mission concepts focused on monitoring to search for seismic waves via airglow (e.g. Garcia et al. 2024). Our model shows that a plume umbrella of an optical thickness of 10 at an altitude of >10 km would result in a radiance reduction of 50 % in the thermal emission background of the $1.27\text{ }\mu\text{m}$ airglow band. Mission concepts involving frequently imaging much of the nightside of Venus at a near infrared window wavelengths such as $1.27\text{ }\mu\text{m}$ present the best chance of detecting an volcanic eruption plume.

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