

CURRENT PROBLEMS AND FUTURE SOLUTIONS FOR IDENTIFYING VENUS' UNKNOWN ABSORBER: K-L. Jessup¹, R. W. Carlson², S. Perez-Hoyos³, Y-J. Lee⁴, F. P., Mills⁵, S. Limaye⁶, A. Roman⁷, N. Ignatiev⁸, L. Zasova⁸, ¹*Southwest Research Institute, Boulder CO, USA, jessup@boulder.swri.edu*, ²*Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California USA, Robert.W.Carlson@jpl.nasa.gov*, ³*Universidad del Pais Vasco, UPV/EHUS, Spain;*, ⁴*Institute of Space and Astronautical Science, Japan Aerospace Agency, Japan;*, ⁵*Australian National University, Canberra, Australia;*, ⁶*University of Wisconsin, Madison, Wisconsin, USA;*, ⁷*Space Telescope Institute, Baltimore, MD, USA;*, ⁸*Space Research Institute for Russian Academy of Sciences, Moscow, Russia*

Introduction: Venus has ubiquitous, always present H₂SO₄-H₂O cloud and hazes of temporally variant abundance and opacity [1-4]. Although images of Venus at visible wavelengths are mundane, UV and IR images reveal complex atmospheric dynamics. UV-visible spectra also reveal absorption from an unknown species (or combination of species [5,6]) that reaches a maximum at 0.33-0.39 μ [5,7-9]. The relative contrast at 0.33-0.39 μ traces Venus' infamous Y feature, as well as the zonal cloud top motion and wind speeds [10]; also, half of the solar energy deposited in the atmosphere results from absorption in this band [11]. As a result, Venus' unknown absorber plays a critical role in the atmospheric energy balance which drives Venus' atmospheric superrotation and climate evolution; and these relationships motivate the need to find its identity [12].

Three Promising Candidates and their problems: *FeCl₃ aerosol:* Models produced by [13] and [14] strongly favors of weak solution of FeCl₃ (<1%) in 80% H₂SO₄ as a candidate for the unknown absorber due to its compatibility with a) the [7] spectrum which lacks significant absorption above 0.5 μ; b) the Pioneer Venus mode 1 aerosol profiles and c) the observed FeCl₃/H₂SO₄ upper cloud layer ratio [14]. FeCl₃ has too strong absorption in UV, so only a weak solution of FeCl₃ (<1%) in 80% H₂SO₄ may be considered. The life time of this solution is of several weeks at room temperature, this fact may explain disappearance of the UV absorption at middle clouds. Similarly, [15] considers the presence of the FeCl₃ aerosol within the clouds and haze based on phase relationships.

The spectrum produced by the FeCl₃ aerosol (within the range of particle sizes and aerosol solutions reasonable for Venus) tends to be sloped shortward of 0.36 μ [8]. VIRTIS, HST and MESSENGER/MASCS data all indicate that the absorption spectrum above regions with low contrast (neither bright or dark) is relatively flat at 0.33-0.39 μ [5,8,9]. The slope of the absorption within cloud top regions with the lowest (darkest) 0.33-0.39 μ is also extremely exaggerated longward of 0.39 μ. And, all the spatially spectra [5,8,9] obtained during the Venus Express era show that absorption longward of 0.5 μ is possible and that its variance correlates with variance in the slope and

overall brightness of the albedo between 0.34 and 0.39 μ. These behaviors imply that over many regions an absorber different/additional to FeCl₃ solution contributes to Venus' cloud top 0.3-0.6 μ albedo.

Sulfur Products: S₂O₂ (OSSO) is expected to exist at the cloud tops and have absorptions near 0.36; but OSSO has a very short lifetime [16]. [5] finds that either S₂O or OSSO may contribute to the unknown absorber spectrum, but cannot fully account for the absorption behaviors observed longward of 0.4 μm; similarly, chemical models show that OSSO cannot alone account for unknown absorber signature at NUV wavelengths [17].

[8] found that Mie scattering of polymeric sulfur (S_x) can reproduce the [7] spectrum as well as other spectra that include absorption longward of 0.5 μ. But, current photochemical models do not predict free sulfur or S_x to be present at altitudes of cloud tops [18]—though inclusion of S₂O₂ can shift peak S aerosol production to 65 km depending on the assumed vertical mixing profile [17]. All current photochemical models fail to either replicate the vertical abundance profiles of SO₂, SO observed during Venus express era between 60 and 100 km altitudes [19-21], or the H₂SO₄ production rate [19,22] and SO₂ profile [17] below the clouds. Until the mechanism(s) controlling the sulfur oxide species profiles is (are) more completely constrained, the role of sulfur chemistry in supplying the unknown absorber remains unresolved.

Biogenic Sources: Surprisingly, recent lab work shows that there are iron based **acid resistant** bacteria that absorb most efficiently at the wavelengths where absorption of an unknown source has been detected at UV, visible and near-IR wavelengths within Venus' clouds [23-24]. These discoveries along with recent models showing the habitability of early Venus [25] motivate renewed speculation regarding the possibility of a biogenic source as a contributor to the Venus' 0.3-0.6 μ albedo spectrum [26]. However, while it is easy to explain how a biogenic source may have been present in the past [25,27] more work must be done to better understand the transport of such a species to the cloud tops and the survivability of a living or fossilized source at the cloud top level over geologic timescales subsequent to Venus' aquatic age [28].

The Role of the Haze: Consideration of all the remotely obtained UV-visible spectra indicates that broad 0.33-0.39 μ NUV absorption occurs ubiquitously at Venus' cloud tops. Analysis of both imaging and spectral data suggests that the altitude and abundance of the H₂SO₄-H₂O submicron haze relative to the unknown absorber is the primary determinant of the albedo levels in the 0.33-0.39 μ band. This implies that the temporal and spatial variances evident in [5,8,9] may result from variability in the particle size, age and/or composition of the primary absorber/scattering species.

Similarly, analysis of long-term high spatial resolution image monitoring of the cloud tops obtained by Venus Express near 0.36 μ implies that boundaries between NUV bright and dark regions are linked to the boundaries along which the cloud top altitude and/or temperature [29-30] vary, and reveal temporal variations in albedo phase relationship [31]. These results imply a link to dynamics and may in fact motivate a link to microphysical if not chemical changes at the cloud tops—i.e., it is likely the abundance and distribution of Venus' submicron sulfuric acid haze was changing and it is even possible that the composition and/or nature of the absorber itself may be highly variant.

The Path Forward: In light of the presented results it is clear that the next large mission to Venus must simultaneously constrain the mechanisms that control the haze scattering properties while tracing the variation in the absorption resulting from the unknown absorber. This requires a combined program of detailed in-situ sampling at 60-70 km altitude supported by remote sensing spectral imaging of cloud top signatures that can measure the aerosol particle sizes and map the UV-visible spectral both above and within the clouds.

Microphysical models of the latitudes and altitudes where the unknown absorber spectrum has been most prominent indicate that Venus' upper haze evolves cyclically over a ~180 day time period [3], therefore the in-situ element must function for a time period of a half cycle (90 days) or longer.

Since the nature (*aerosol and/or gas or potentially even biogenic*) and composition of the unknown absorber(s) determines its optical depth with altitude, its relative reactivity (chemical and/or kinetic), the time-scale on which it might transform (or age) under different atmospheric conditions, as well as its sensitivity to the vertical and horizontal transport time scales --it is important to design observations that are able to trace each of these conditions. Analysis of both ground and space based data indicates that the altitude of the NUV absorber is in the upper cloud, at altitudes equivalent or just below the cloud top altitude (which has been sensed at altitudes ~ 72±4 km, depending on the date of observation)—but the true vertical profile of the

unknown absorber remains ill-constrained. Thus, exploration of the nature of Venus' UV and visible absorbers in the 60-70 km region must be achieved.

Tracing the relative importance of the atmospheric dynamics and chemistry will require detailed measure of the atmospheric structure and both the horizontal and vertical wind shears will be required over time scales consistent with the evolution of Venus' cloud formation. Tracing the scattering and absorption properties above and within the cloud a well suited set of in-situ and remote sensing spectrometers, polarimeters, as well as in-situ nephelometers. Lastly, confirming/refuting the presence of a biogenic signature can be straightforwardly achieved by using accurate microimagers tuned to detect fluorescence at wavelengths unique to organic/biogenic materials [32].

References: [1] Hansen and Hovenier, (1974) *J AtmosSci*, 31, 1137. [2] McGouldrick, K. and Tsang, C. C. C. (2017) *Icarus*, 286, 118–133. [3] Gao et al. 2014, *Icarus*, 231, 83-98. [4] Parkinson et al. 2015, *PSS*, 113, 205-218 [5] Perez-Hoyos et al., (2017) *JGR-Planets*, doi/10.1002/2017JE005406 [6] Krasnopolsky 2018. [7] Barker, E. S., et al. (1975). [8] Carlson, et al. (2016) *International Venus Conference*, Oxford, UK [9] Jessup et al. 2017 (AGU) [10] Rossow 1980, *JGR*, 85, 8107-8128; [11] Crisp, D. (1986). *Icarus*, 67, 484-514; [12] Lee et al., (2017) Venus Modeling Workshop, Moscow, Russia [13] Zasova, L. (1981) *Adv. Science Research*, 1, 13-16; [14] Krasnopolsky, V. A., (1986/2017) *Icarus* 286, 134–137 [15] Petrova et al. (2017), *PSS*, 113, 120-134. [16] Fransen, B. N., et al. (2016). *Geophys. Res Letters*, 43, 11146-11155. [17] Krasnopolsky 2018, *Icarus*, 299, 370-385; [18] Krasnopolsky, V. A. (2016) *Icarus*, 274, 33-36; [19] Vandaele, A. C. et al. (2017) *Icarus*, 295, 1-15; [20] Krasnopolsky, 2015 *Icarus*, 252, 327-333; [21] Jessup et al. 2015; [22] Krasnopolsky 2012, *Icarus*, 218, 230-246; [23] Ossa et al. (2011) *Process Biochemistry*, 46 1335-1341 [24] Więckowski, A. B., et al. (1999). *Applied Microbiology and Biotechnology*, 52, 96-98 [25] Way, M. J. (2016) *Geophys. Res. Letters*, 43, 8376; [26] Limaye, S. S., (2017) Venus Modeling Workshop, Cleveland, OH, USA; [27] D. H. Grinspoon and M.A. Bullock (2007) *Astrobiology and Venus Exploration* In: Esposito, L., Stofan, E.R., Cravens, T.E. (Eds.), *Exploring Venus as a Terrestrial Planet* [28] Schulze-Makuch, D., et al., (2014) *Extraterrestrial Life: What are We Looking For?* In: (Vera Kolb ed) *Astrobiology: An Evolutionary Approach*, CRC Press; [29] Ignatiev, et al. (2009). *J. Geophys. Res.* 114. E00B43 [30] Lee et al. (2012), *Icarus*, 217, 599-609. [31] Lee et al. (2015) *Icarus*, 253, 1-15; [32] Yagamishi et al. (2016) *JSASS Aerospace Tech. Japan*, 14, 117-124