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ADVANCING VENUS ATMOSPHERIC MODELING VIA COORDINATED HST-AKATSUKI OBSERVATIONS. K. L. Jessup¹, T. Imamura², M. Nakamura², F. Mills³, E. Marcq⁴, S. Limaye⁵, C. Wilson⁶, J.L. Bertaux⁴, E. Young¹, and T. Kremic⁷, ¹Southwest Research Institute 1050 Walnut Street, Suite 300 Boulder CO 80302 USA, jessup@boulder.swri.edu; ²Institute of Astronautical Science Japan Aerospace Exploration Agency 3-1-1, Yoshinodai, Chuo-ku, Sagamihara, Kanagawa 252-5210, Japan; ³Space Science Institute, Boulder, CO, 80303, USA; ⁴Maître de Conférences LATMOS / Univ. de Versailles Saint-Quentin-en-Yvelines Bureau 1221, Bâtiment OVSQ 11 Boulevard d'Alembert, F-78280 Guyancourt, France; ⁵University of Wisconsin-Madison, Madison, WI 53706, USA; ⁶Atmospheric Physics Clarendon Laboratory Parks Road Oxford OX1 3PU; ⁷NASA Glenn Research Center, 21000 Brookpark Rd, Cleveland, OH 44135, USA.

Introduction: Venus' global-scale H₂SO₄ cloud and haze layers form via the combination of SO₃ and H₂O, and SO₃ forms via oxidation of SO₂. Sulfur-bearing and sulfur-oxidized species, such as SO₂, SO, S, OCS, H₂SO₄, are key traces of Venus' H₂SO₄ cloud/haze formation process. These species are also important tracers of the on-going chemical evolution of Venus' atmosphere, atmospheric dynamics, and the level/history of active volcanism occurring on the planet. However, the specific pathways (which may be chemical, microphysical and/or dynamical) that balance the budget of sulfur (and oxidized sulfur) in Venus' atmosphere are ill-defined, as are the mechanisms that sustain the density of the clouds. As result, Venus' climate evolution is ill-defined, and understanding Venus' sulfur-budget is highlighted as an important Venus exploration target.

Objective of the Akatsuki Mission: The Japanese Space Agency's (JAXA) *Akatsuki* mission was successfully inserted into an equatorially centered Venus orbit trajectory on December 7, 2015. The primary objective of the mission is to understand Venus' atmospheric dynamics, cloud chemistry and cloud physics by observing key characteristics of Venus' atmosphere from above and below the 47-70 km cloud layer on both the day and night side. Using a suite of 4 cameras: the 1 μm IR (IR1), 2 μm IR (IR2), the UV Imager (UVI), and the Long wavelength IR (LIR) Camera, which collectively have sensitivity in the UV, visible and infrared, *Akatsuki* will obtain images of Venus' small scale cloud features to derive detailed measurement of the wind field at and below the cloud tops and to study in detail convection within the clouds. *Akatsuki* will also use the UVI to record the spatial distributions of SO₂ and Venus infamous, but as yet unidentified, 365 nm UV absorber and their relationships with the cloud structure and the wind field. Additionally, *Akatsuki* will record cloud opacities at 2.26 and 1.73 micron. These data will be analyzed together with the IR1 1.01-micron and 0.90-micron images with the aid of radiative transfer calculation to determine the spatial and temporal variations in the cloud particle

size and density [1]. Likewise, details of the haze properties will be derived from UVI limb imaging.

Coordinated Observation Motivation: In order to understand and interpret the spatial distributions SO₂ and the 365 nm UV absorber that will be mapped by *Akatsuki* the chemical cycles of each of these species must be understood. However, since the chemical composition (let alone physical state aerosol/gas) of the 365 nm absorber has not yet been identified, it is difficult to uniquely identify the chemical, dynamical and/or microphysical processes that may drive its variability and distribution. Additionally, *Akatsuki* does not have a way to directly map other sulfur-bearing species such as SO, OCS or H₂SO₄ that are key players in the sulfur cycle and H₂SO₄ formation processes.

In order to support *Akatsuki*'s goal to understand the cloud chemistry and cloud formation process and in order to understand how these processes relate to transport (zonal, vertical and/or meridional) we are proposing to obtain complementary and coordinated HST spectral and imaging observations of Venus' dayside atmosphere in the 200-600 nm wavelength region. The HST images will provide high (20±2 km) spatial resolution mapping of Venus' dayside SO₂ gas absorption signature below 240 nm, the 200-400 nm cloud top brightness/ contrast, and the distribution of the unknown UV absorber as a function of local time at each latitude. The HST spectra will provide at high (50±10 km) spatial resolution, which is comparable to the expected UVI image spatial resolution at *Akatsuki* apoapsis, detailed latitude and local time detections of i) the SO₂ and SO gas absorption signatures at wavelengths < 240 nm, at high (0.27 nm) spectral resolution ii) the long-wavelength (280-330 nm) SO₂ absorption signature at high (0.27 nm) spectral resolution, and iii) the 340-400 nm spectral signature of the unknown UV absorber at medium (0.54 nm) spectral resolution. The spectral data will also provide a means to validate/accurately complete radiometric calibration of the UVI images.

HST is the only telescope in operation that has sensitivity below 240 nm, where the continuum signature of the unknown UV absorber is negligible, with

sufficient spectral resolution to allow the reliable coincident retrieval of the SO₂ and SO gas distributions as a function of latitude and local time. These HST-unique measurements make feasible the accurate interpretation of the role of photochemical processing relative to dynamical and microphysical processes on Venus' SO₂ gas distribution. Additionally, the availability of the 350-400 nm HST spectral data should greatly improve our ability to identify the source of the 350-400 nm absorption, and accurately define the overall opacity produced by this absorber at each latitude and local time. Likewise, the 280-330 nm spectral data will provide needed validation of the SO₂ retrievals derived from the 283 nm *Akatsuki* /UVI images.

Thus, the detailed imaging and spectral measurements obtainable by HST can provide needed complementary and supplemental data not independently obtainable by *Akatsuki*.

Anticipated Science Return: Multiple observations of Venus' cloud tops were made by the *Venus Express* (VEx) suite of instruments and ground-based and space observatories such as the James Clarke Maxwell Telescope (JCMT), Atacama Large Millimeter/sub-millimeter Array (ALMA) Telescope and the Hubble Space Telescope (HST) and Infrared Telescope Facility (IRTF) during the VEx-era. These observations revealed that Venus's sulfur-oxide species exhibited unexpected spatial patterns and spatial/temporal variability [2-5] that have not been satisfactorily explained by models. Of particular import were the HST/STIS, JCMT, and ALMA observations which showed for the first time that at least one other significant sulfur reservoir (in addition to SO₂ and SO) must be present throughout the 70-100 km altitude region to explain i) the positive correlation between SO₂ and SO variations [2] and ii) the inversion in the SO₂ vertical profile at ~80 km, leading to the unexpected increase in the SO₂ abundance above ~80 km [6,7]. Additionally, the combined HST [2], JCMT [2, 6], ALMA [7] and IRTF observations [5] suggest that there is a minimum inflection point in the SO₂ abundance between 70 and 80 km [8]. No photochemical model has an explanation for this behavior [8]. Some General Circulation Models (GCMs) indicate that dynamics may play an important role in generating an inflection point at 75 km altitude, but do not provide a definitive explanation of the source of the inflection at all local times or latitudes [8,9].

Acquisition of coordinated HST and *Akatsuki* observations will result in a detailed record of Venus' pole-to-pole SO₂ gas density, aerosol opacity, and UV absorber distributions at each latitude as a function of local time in the 60-80 km altitude region without temporal confusion relative to the coincident wind field data recorded by *Akatsuki* at each latitude near 65±5

km. Detailed modeling of these observations can provide new insights into the likely balance between chemical, microphysical, and dynamical processes active throughout Venus' 70-100 km altitude region, e.g., see [2, 10]. Therefore, the proposed new coordinated observations have the potential to address the very issues raised by observations taken during the VEx-era.

Moreover, additional new coincident and coordinate ground and balloon-based observations made at submm and IR wavelengths can provide additional mapping of the distribution of SO₂ as a function of local time, latitude and cloud motion in the upper troposphere (30-60 km) and mesosphere (60-90 km) relative to the distributions of other sulfur-oxide species (such as SO and OCS), without any temporal disparity or confusion. The addition of this empirical data can allow the relationship between chemical/microphysical processing and vertical transport and circulation through adjacent altitude regions to be studied and modeled with greater accuracy.

Details of the haze properties derived from analysis of limb brightness signatures captured in the 365 nm *Akatsuki* images can also be fed into Mie scattering models to define the impact of the aerosols on the photon (=radiation) budget as function of altitude at each local time observed. The combination of the HST derived SO₂ and SO gas observations with the radiation budget results can be fed into photochemical and microphysical models and used to investigate the impact of H₂SO₄ formation on Venus' overall sulfur budget. This has the potential to improve our overall understanding of the cloud formation process which in turn impacts modeling of Venus' long term climate evolution.

Summary: The successful insertion of *Akatsuki* into Venus orbit on December 7, 2015 has opened up a new epoch of continuous Venus observation. This in turn provides a new opportunity to obtain coordinated observations that can capitalize, in concert, on the unique capabilities of the *Akatsuki* suite of instruments as well as other ground and space-based observing platforms, enhancing and expanding the science return of each observation.

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