Advancing Venus Atmospheric Modeling via Coordinated HST-Akatsuki Observations

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Introduction: Venus' global-scale H_2SO_4 cloud and haze layers form via the combination of SO_3 and H_2O, and SO_3 forms via oxidation of SO_2. Sulfur-bearing and sulfur-oxidized species, such as SO_2, SO, S, OCS, H_2SO_4, are key traces of Venus' H_2SO_4 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) *Akatuski* 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 SO_2 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 SO_2 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 H_2SO_4 that are key players in the sulfur cycle and H_2SO_4 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 SO_2 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 SO_2 and SO gas absorption signatures at wavelengths < 240 nm, at high (0.27 nm) spectral resolution ii) the long-wavelength (280-330 nm) SO_2 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 SO_2 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' SO_2 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 SO_2 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 SO_2 and SO) must be present throughout the 70-100 km altitude region to explain i) the positive correlation between SO_2 and SO variations [2] and ii) the inversion in the SO_2 vertical profile at ~80 km, leading to the unexpected increase in the SO_2 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 SO_2 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 SO_2 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 *Akatasuki* 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 SO_2 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 *Akatuski* 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 SO_2 and SO gas observations with the radiation budget results can be fed into photochemical and microphysical models and used to investigate the impact of H_2SO_4 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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