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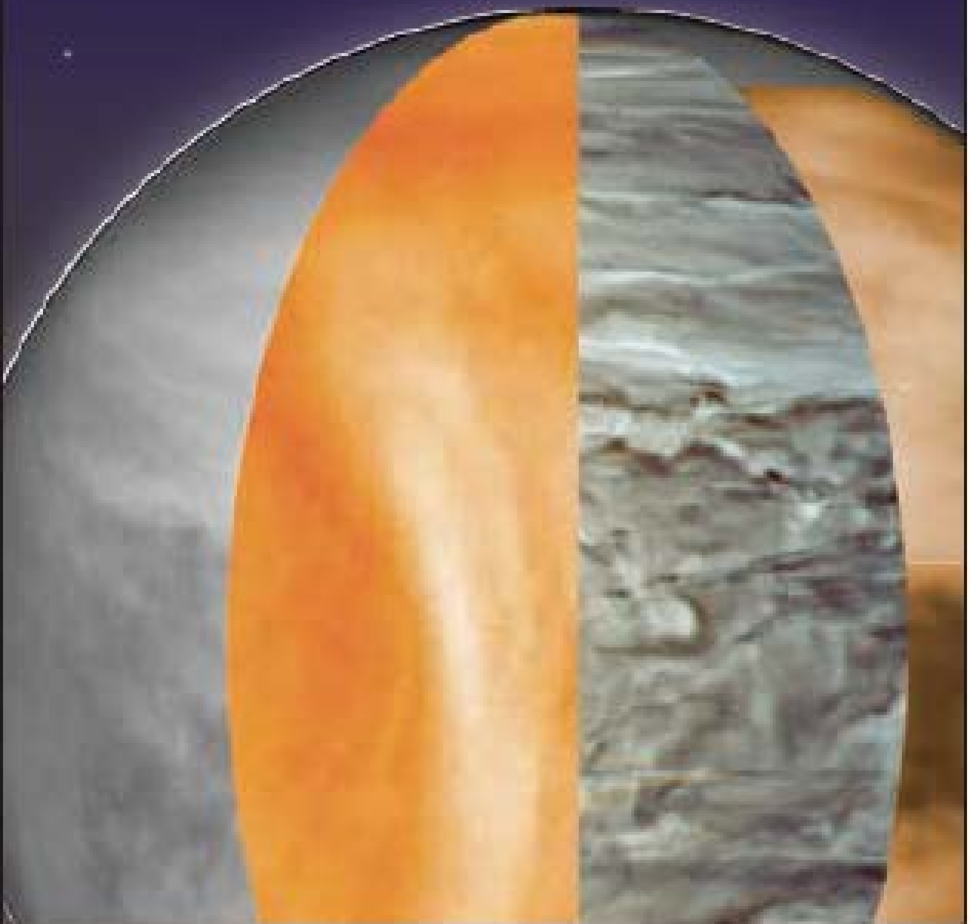

ABSTRACTS

Session 01

Solid body/Geology

VENUS INTERIOR AND SURFACE TODAY

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Introduction: Some of the key questions for understanding the evolution of Venus are: Why does Venus lack plate tectonics? How does it lose heat? Did it resurface catastrophically? How are the interior, surface, and atmosphere coupled? What geologic processes are active today? We discuss these questions in light of VIRTIS surface emissivity studies of coronae, hotspots, proposed subduction zones, as well as resurfacing studies. We propose that Venus has local, ongoing resurfacing via processes such as hotspot volcanism, subduction and delamination.

Resurfacing: Constraining the resurfacing history of Venus is challenging due to the limited number (~1000) of impact craters. Combining additional constraints from observations of dark floored craters [1,2] or removal of extended ejecta [3] argues for ongoing, equilibrium rather than catastrophic resurfacing at the scale of 100s to 1000s of km.

Subduction & Plate Tectonics: Subduction is the necessary first step in initiating plate tectonics. Subduction was proposed to occur on Venus [4-6], but the presence of features produced by mantle plume at many of the sites brought this interpretation into question [7]. More recently plume-induced subduction has emerged as a key hypothesis for initiating terrestrial plate tectonics [e.g. 8]. Recent laboratory experiments have demonstrated how plume-induced subduction operates on planets; the predicted characteristics match many subduction features on Venus remarkably well [9]. Further, this process acts to recycle the entire lithosphere and resurface local areas on the scale of 100s to 1000s of km.

Yet subduction has not produced plate tectonics on Venus. Many have proposed that the interior of Venus is dry, and that this makes the lithosphere too strong to break [e.g. 10 & refs]. However, this hypothesis needs to be reexamined, given evidence that planets form wet [11], as well as evidence for at least locally weak lithosphere [e.g. 12] and limited volatile loss [e.g. 13]. Alternatively, hot lithosphere may allow the lithospheric scale faults produced by subduction to anneal overtime [14]. If faults that break the entire lithosphere cannot be maintained, they cannot lead to the network lithospheric-scale faults needed for plate tectonics.

Emissivity: The VIRTIS instrument on Venus Express measured the surface brightness temperature at 1.02 um for much of the s. hemisphere, from which emissivity can be derived [15]. Areas of high emissivity have been interpreted as evidence of recent, unweathered basalt, implying geologically recent activity [16]. Such areas are in locations previously interpreted as underlain by a mantle plume based on the geology, topography, and gravity data [e.g. 17], corroborating the interpretation of recent volcanism. At least one of these sites has evidence of plume-induced subduction [9].

Venus Today: Surface emissivity provides evidence of recent volcanism. Changing levels of SO_2 in the atmosphere may reflect volcanic outgassing [18]. These volcanic sites are directly linked to the interior, as the volcanism occurs at sites of mantle upwelling, with at least one showing evidence of subduction. These observations suggest gases are currently being released from the in the interior and possibly recycled back into the interior. Volcanism is still actively resurfacing Venus, consistent with equilibrium resurfacing. Thus Venus is best characterized as in a sluggish convective regime. Further, early Earth, with its hot lithosphere, may well have experienced a similar state before the start of plate tectonics [9].

Major progress on understanding the evolution of Venus would be enabled by high resolution topography, radar imaging, interferometry to look for active deformation and near infrared spectroscopy. These measurements would resolve the processes modifying craters, resurfacing the planet, and driving activity today.

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Numerical simulations of mantle convection with crust formation, implications for the dynamics of Venus

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Crust production is sometimes estimated in global geodynamics simulations of mantle convection but is often considered to be have little impact on the dynamics. We present here a set of studies where crust is formed and is shown to have a first order influence on the convection regime.

We show that basaltic crust production and the style of magmatism (eruptive opposed to intrusive) have to be considered to fully capture the thermo-compositional evolution of terrestrial planets. We show that boundary layer theory can be updated to take crustal thickness and crust recycling into account.

3D numerical simulations of the last overturn of Venus will then be presented. We address the question of the geometry and amount of crustal material left behind a massive mantle overturn, as the cratering of Venus indicates it might have happen on Venus ~500 Myrs ago.

A two-stage evolution model of Venus' mantle and its implications for the Earth

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We developed a series of numerical models of magmatism in a convecting mantle with a stagnant lithosphere to understand the evolution of Venus' interior. Magmatism occurs as a permeable flow of basaltic magma generated by decompression melting through the solid mantle, and the solid-state convection of the mantle with temperature-dependent Newtonian rheology is affected by the garnet-perovskite transition and the post-spinel transition. In our preferred models, the mantle evolves in two stages: On the earlier stage, the solid-state convection occurs as a layered convection punctuated by repeated bursts of hot materials from the lower mantle to the surface. The bursts induce vigorous magmatism that forms the basaltic crust, enriched in heat-producing elements (HPEs). A part of the basaltic crust recycles into the mantle and accumulates along the post-spinel boundary to form a barrier to the convective flow; the barrier occasionally collapses to cause the bursts. On the later stage when the HPEs have already decayed, in contrast, the basalt barrier disappears and whole-mantle convection occurs more steadily. Mild magmatism is induced by small-scale partial melting at the base of the crust and hot plumes from the deep mantle. The internal heating by the HPEs that recycled into the mantle in the earlier stage allows the magmatism of the later stage to continue throughout the calculated history of mantle evolution. The two-stage evolution model meshes with the observed history of magmatism and the lithosphere on Venus. By implementing a model of tectonic plates to this model of Venus, I also obtained a two-stage evolution model of the Earth's mantle that meshes with observed features of the Earth's history. On the earlier stage that continues for 1-2 billion years, tectonic plates move chaotically due to repeated bursts of hot materials from the lower mantle. On the later stage, however, plate motion becomes steadier, as mantle bursts subside.

Signatures of lithospheric flexure and elevated heat flow in stereo topography at coronae on Venus

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Signatures of lithospheric flexure were previously identified at more than a dozen large coronae on Venus. Thin plate models fit to topographic profiles return elastic parameters, allowing derivation of mechanical thickness and surface heat flows given an assumed yield strength envelope. However, the low resolution of altimetry data from the NASA Magellan mission has hindered studying the vast majority of coronae, particularly those less than a few hundred kilometers in diameter. Here we search for flexural signatures around 99 coronae over ~20% of the surface in Magellan altimetry data and stereo-derived topography that was recently assembled from synthetic aperture radar images. We derive elastic thicknesses of ~2 to 30 km (mostly ~5 to 15 km) with Cartesian and axisymmetric models at 19 coronae, including some that are not presently classified as having a topographic rim or outer rise. We discuss the implications of low values that were also noted in earlier gravity studies. Most mechanical thicknesses are estimated as <19 km, corresponding to thermal gradients >24 K km^{-1}. Implied surface heat flows >95mW m^{-2}—twice the global average in many thermal evolution models—imply that coronae are major contributors to the total heat budget or Venus is cooling faster than expected. Binomial statistics show that "Type 2" coronae with incomplete fracture annuli are significantly less likely to host flexural signatures than "Type 1" coronae with largely complete annuli. Stress calculations predict extensional faulting where nearly all profiles intersect concentric fractures. We failed to identify systematic variations in flexural parameters based on type, geologic setting, or morphologic class. Obtaining quality, high-resolution topography from a planetwide survey is vital to verifying our conclusions.

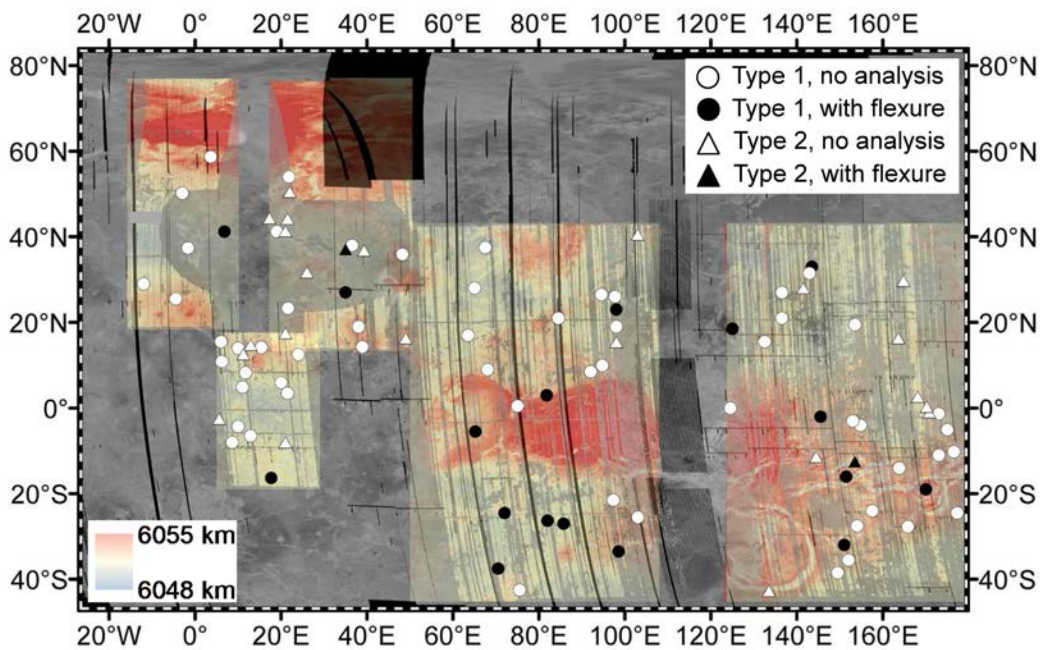

Figure | Map of our study area. Colored topography plotted over greyscale radar images from NASA Magellan. Black symbols indicate the coordinates of coronae with flexural signatures (O'Rourke & Smrekar, *J. Geophys. Res. Planets* **123,** 369–389, 2018).

Self-Consistent Reference Seismological Models for Determining Venus's Interior Composition

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Venus is the only rocky planet in our solar system with a mass and radius most similar to that of the Earth. Despite this similarity, however, we know remarkably little about its internal structure. Basic physical data, like Venus's moment of inertia are unknown, as is the size of its core. Likewise, we lack good estimates of the temperature of Venus's mantle and core, even though these quantities are important for understanding why superficially similar Venus is different to the Earth. As we look elsewhere in the Galaxy and see exoplanets with radii and masses similar to those of the Earth, it is imperative that we are able to understand the diversity of terrestrial planets in our own solar system.

We derive several coupled compositional-seismological reference models for Venus's interior, corresponding to different compositions and a range of mantle potential temperatures (Figure 1). The ExoPlex and BurnMan software packages are used to consistently calculate both the composition and mineralogy of Venus as a function of radius (and thus pressure), as well as the seismic velocity and density profiles for each model (Figure 2).

For each model we calculate ray theoretical travel times for phases sensitive to both the mantle and the core, as well normal mode centre frequencies. We also compute seismic waveforms for each model. We investigate seismic phases which are sensitive to the depth of the core-mantle boundary beneath Venus's surface. We also assess the variation of mantle transition zone thickness between our different reference models as a function of mantle temperature.

We outline a series of potential seismological instruments that, with the aid of technological improvements, will allow us to explore Venus's interior. While these missions will be difficult, we show different self-consistent interior models of Venus give rise to different seismological observations. This suggests that these future geophysical missions may provide an abundant data set to allow us understand our planetary sibling, and in turn the Earth itself.

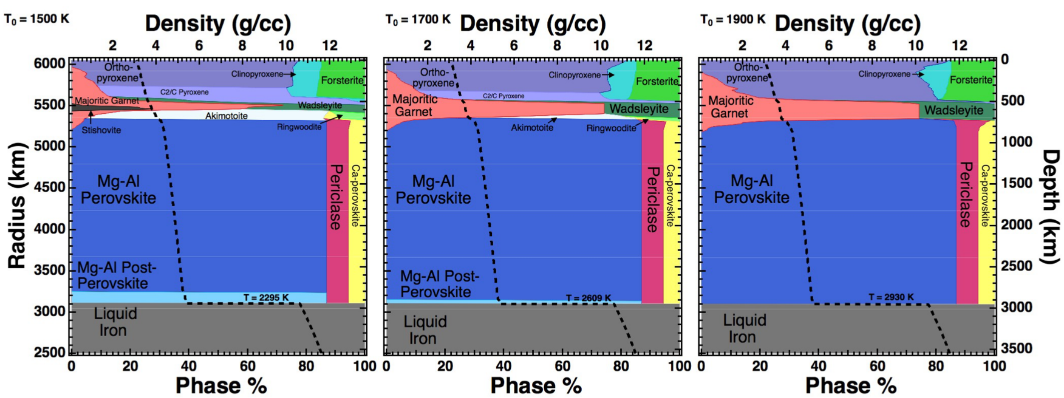

Figure 1: Planetary phase diagrams calculated by ExoPlex for a Venus-size planet of solar composition. Models are calculated using mantle potential temperatures of 1500 (left), 1700 (middle) and 1900 K (right). Density as a function of depth is shown as a dashed black line.

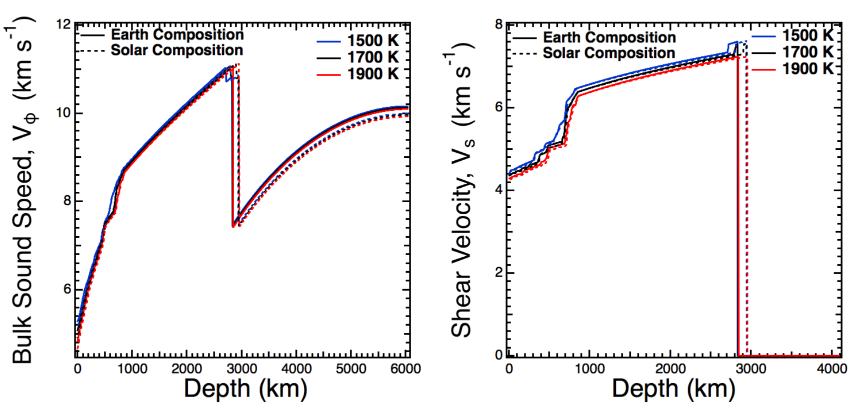

Figure 2: Calculated bulk sound speeds (V_ϕ), shear velocities (V_s) and densities for each Venusian Compositional Model.

Plume-induced subduction and ridge dynamics in the expanding Artemis Coronae

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Venus today presents no large-scale network of subduction trenches and accretion ridges, which is the signature of plate tectonics on Earth. On the other hand, Venus relatively young surface points towards either a quite recent catastrophic renewal of the whole planet surface, or the continuous renewal of small areas. Using laboratory modeling, we show here that the latter could be produced by plume-induced subduction [1,2] and accretion [3], one exemple being Artemis Coronae (fig.1).

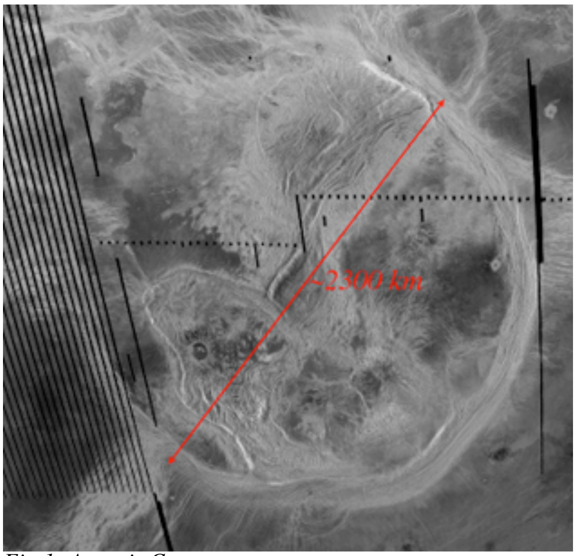

Fig.1: Artemis Coronae

Laboratory experiments: We use colloidal aqueous dispersions of silica nanoparticles. Their rheology depends strongly on the solid particle fraction, φ_p, deforming in the Newtonian regime at low φ_p, and transitioning to strain-rate weakening, plasticity, elasticity, and brittle properties as φ_p increases [4]. So, as the system is dried from above, a dense skin grows on the surface, akin to a planetary lithosphere (fig.2a). When it is also heated from below, hot plumes develop. When a hot plume impinges under the skin (fig.2b), it triggers a new mode of subduction: as the upwelling plume material breaks the lithosphere and flows above the denser skin, it forces it to sink. The subduction trenches are localized along the rim of the plumes and strong roll-back is observed (fig.2b). Subduction always occurs along partial circles, which is due to the brittle character of the upper part of the experimental lithosphere [2].
Moreover, as roll-back subduction proceeds, the coronae expands and an accreting ridge system develops inside the coronae. The ridge shape is governed primarily by the axial failure parameter Π_F, which depends on the spreading velocity, the mechanical strength of the lithospheric material and the axial elastic lithosphere thickness [3]. Experiments with the largest Π_F present quite unstable ridge axis with a large lateral sinuosity and the formation of numerous microplates (fig.2c).

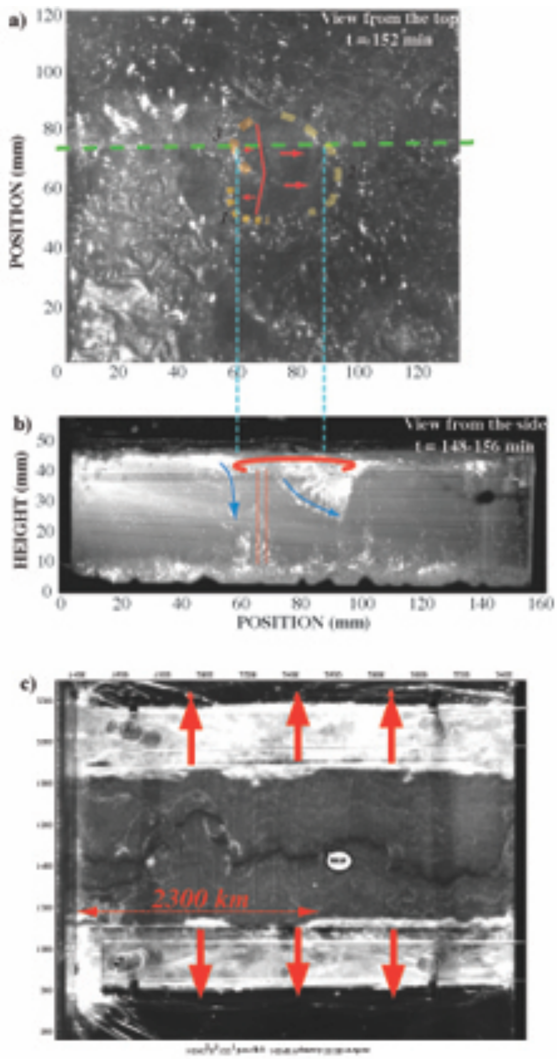

Fig.2: a,b) Plume-induced subduction; c) ridge shape for high spreading velocity and/or thin axial elastic thickness.

Scaling laws derived from the experiments quantitatively predict the observations at Artemis Coronae.

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Session 02

Evolution (1) Solid Body

FAULT ANALYSIS OF VENUS RIDGE BELTS USING STEREO-DERIVED TOPOGRAPHY. J. A. Balcerski[1], P. K. Byrne[2], [1]NASA Glenn Research Center, Cleveland, OH. (jeffrey.balcerski@nasa.gov), [2]North Carolina State University, Raleigh, NC.

Introduction: Ridge belts on Venus are relatively narrow, elevated features generally tens of km wide, up to thousands of km in length, and with vertical expressions of hundreds of meters [e.g. 1–3]. These belts often border and delineate expansive lower-lying and relatively featureless plains and are often found in, or grade into, tesserae and dorsae. The relative timing of formation of ridge belts does not appear to be confined to a specific chronologic period, nor is there a clear universal relationship between belt formation, local radar-bright lineaments, surrounding terranes, and other regional structures [2]. Mechanisms of formation are difficult to determine from Magellan GTDR data, but the recent availability of stereo-derived topography for ~20% of the planet at an optimal resolution of 1–2 km/px [4] provides an opportunity to differentiate between symmetric and asymmetric ridges, and to develop a better understanding of the relationship between radar-bright lineations and the ridge (and surrounding) topography.

Location: We selected a relatively undeformed region bounded by ridge belts that were well-resolved in both the Magellan GTDR and Herrick et al. [4] topographic products, as well as the 75 m Magellan FMAP mosaics. This feature, situated at -19.4°N, 68.0°E, is bounded by Dylacha Dorsa on the western edge and Wala Dorsa on the eastern side. Xi Wang-Mu and Manatum Tesserae form the southern and northern margins, respectively. This location has not been specifically described in prior analyses, but the dorsae bear characteristics similar to the "broad arch" categorization of Frank and Head [2], with an average width around 50 km and length of about 1500 km.

Process: We constructed several topographic profiles oriented as close to perpendicular to the belt strike as the topo data permitted. These data have resolutions that are highly variable, so we selected profiles from those locations with the highest resolution (in this case, ~1.5 km/px). The resulting profiles were compared with those over the same sections using GTDR data. With the increased resolution provided by the stereo data, we were able to compare locations of the radar-bright parallel/subparallel lineations within the belt structure with the topographic expression of the belt. These profiles were then inspected for any apparent (a)symmetries; where possible, ridge slopes were then measured.

Topographic analysis*:* Although data from the GTDR are insufficient to distinguish between symmetric and asymmetric character of the ridge, the stereo data clearly show that the ridges are composed of asymmetric flanks with multiple peaks and valleys. Given the strikingly similarity to lunar and Martian wrinkle ridges [2, 5–8], we use a similar numeric elastic continuum model as previous studies [e.g., 9] to place estimates on the subsurface geometry of the underlying fault(s).

Results: The asymmetry of radar-bright lineations, present only on the southeast side of the ridge axis and decreasing in density with distance away from the ridge, suggests that these lineations are small-scale ridges whose surface brightness was enhanced by fracturing during compression. This fabric, and the associated production of intraridge peaks and valleys, may represent imbricate fans and thus suggests crustal shortening along a décollement. Given the canonically inferred low water content of Venusian crustal materials [e.g., 10], and as the planet's surface is equivalent to a low metamorphic grade environment, it is unlikely that this detachment surface exists because of volatile pore pressure or poorly consolidated strata. We presume that this surface more likely represents Venus' relatively shallow brittle–ductile transition [e.g., 11]. The results of our use of the to numerically model plausible fault geometry with the COULOMB software toolkit to numerically model plausible fault geometry largely support this interpretation: our best-fit models suggest that these ridges are fault-propagation folds atop an extended horizontal fault at around 6 km below the surface, which terminates about 1 km below the ridge. Further modeling will indicate whether this depth is specific to this locale, or characteristic of Venus' ridge belts in general.

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MINERAL SPECTROSCOPY OF THE SURFACE OF VENUS

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Introduction: Recent advances now permit information about mineralogy of the surface of Venus to be obtained either from orbit or from in situ instrumentation on the surface. We review here likely mineral species on Venus, and discuss instrumentation relevant to their detection.

Mineralogy: Primary Venus surface mineralogy is likely controlled by basaltic glass and its crystallization products, including olivine (forsterite), high- and low-Ca pyroxene (diopside, enstatite), plagioclase feldspar, and Fe oxides [1]. Minor phases may include K-feldspar, fluorapatite, pyrrhotite, and amphiboles [2]. If the tessera highlands are more felsic, then K-feldspars and quartz are likely to be far more abundant. Depending on parent rock type, weathering products could include Fe oxides (hematite), Ca sulfate, chlor-apatite, pyrite, andalusite, sodalite, and cordierite.

In high-elevation areas of Maxwell Montes, the sharp 'snow line' transition to high radar backscatter could be caused by alteration to pyrite or other chalcogenide. Elsewhere (Ovda regio, Tepev volcanoes), changes in radar backscatter with elevation could arise from the ferroelectric character of chlorapatite, a weathering product of igneous fluorapatite [3], suggesting that these regions could be composed of more felsic rock types that are lower in total iron content.

In-situ analyses: X-ray diffraction is the standard method for identifying minerals. As implemented, XRD requires ingestion of sample powder and long durations (~10 hours) [4], both of which may be impractical on Venus' surface.

Raman scattering is diagnostic for molecular groups (e.g., CO_3^{2-}) and covalent bonding, allowing detection of very low abundances of carbonates, phosphates, sulfates even in glass matrices [5]. Most silicates, dominated by ionic bonds, can be detected at modal abundances ≥3% [6]. Raman modes are insensitive to pressure and shift only slightly with temperature [7], so existing spectral libraries acquired under ambient conditions can be used for mineral identification. However, Raman detection of phases opaque to laser light (e.g., sulfides, Fe oxides, some Fe-rich silicates) is quite limited.

Mineralogy from orbit: Relatively transparent NIR 'windows' in Venus' dense CO_2-rich atmosphere (~0.86, 0.91, 0.99, 1.02, 1.11, and 1.18 μm) permit nighttime orbital imaging of light emitted by the surface. Those six bands may permit mineral identification in a manner similar to the CRISM instrument on Mars (11 channels).

To measure optical band shifts with temperature, emissivity measurements of rock standards and various mineral species are being collected at DLR [8,9]. Binary classifiers [9] demonstrate that at current best estimate errors, basalt spectra can be easily discriminated from basaltic andesites, andesites, and rhyolite/granite. Fe-bearing silicates have high VNIR emissivity, allowing discrimination of mafic (Fe-rich) and felsic rocks even with only the 0.99 and 1.02 μm bands. Rocks low-Fe silicates that may contain Fe oxides (rhyolite, granites) also have negative slopes from 0.86 to 0.91 μm. Surface weathering by oxidation can detected from several band ratios; e.g., hematite is easily distinguished from magnetite and pyrite from 0.99 to 1.02 μm [10].

Summary: Technology exists to make mineralogical measurements of Venus both *in situ* and from orbit. Deeper laboratory databases with appropriate surface materials and mixtures thereof for both VNIR emissivity (at high temperature) and Raman (ambient) will be useful to increase science return from Venus missions.

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The Spectroscopy of the surface of Venus –in the laboratory and from orbit. J. Helbert[1], M. D. Dyar[2,3], A. Maturilli[1], T. Widemann[4], E. Marcq[5], D. Wendler[1], I. Walter[6], M. D'Amore[1], S. Ferrari[7,1], N. Müller[8], S. Smrekar[8], [1]Inst. for Planetary Research, DLR, Berlin, Germany (joern.helbert@dlr.de), [2] Planetary Science Institute, Tucson, AZ, USA, [3]Dept. of Astronomy, Mount Holyoke College, South Hadley, MA USA, [4]LESIA, Observatoire de Paris, France [5]LATMOS, Université Paris-Saclay, France, [6]Institute for Optical Sensor Systems, DLR, Berlin, Germany, 7University of Padova, Padova, Italy, [8]Jet Propulsion Laboratory, Pasadena CA, USA.

Introduction: Many efforts have been made since the landing of Venera 9 and 10 [1] to obtain optical spectra of Venus analog materials at relevant temperatures. [2] provided a first set of reflectance measurements of basaltic materials in the spectral range from 0.4 to 0.8 µm. Since then, all efforts to extend these measurements to longer wavelengths have stalled.

It was commonly accepted that compositional data could only be obtained by landed missions because Venus' permanent cloud cover prohibits observation of the surface with traditional imaging techniques over most of the visible spectral range. Fortuitously, Venus' CO_2 atmosphere is actually partly transparent in small spectral windows near 1 µm. These windows have been used to obtain limited spectra of Venus' surface by ground observers, during a flyby of the Galileo mission at Jupiter, and from the VMC and VIRTIS instruments on the ESA VenusExpress spacecraft. In particular, the latter observations have revealed compositional variations correlated with geological features [3-8].

These observations challenge the notion that landed missions are needed to obtain mineralogical information. However, any interpretation in terms of mineralogy of VNIR spectroscopy data from orbiters requires spectral libraries acquired under conditions matching those on the surfaces being studied.

Venus facility at PSL: The Planetary Spectroscopy Laboratory (PSL) at DLR took up this challenge, building on nearly a decade of experience in high temperature emission spectroscopy in the mid-infrared [9-11]. After several years of development and extensive testing, PSL is now in routine operation for Venus-analog emissivity measurements from 0.7 to 1.5 µm over the whole Venus surface temperature range.

PSL has started a database of Venus analog spectra including measurements of rock and mineral samples covering a range from felsic to mafic rock and mineral samples [12]. This first set already shows the potential for mapping of Venus mineralogy and chemistry *in situ* from orbit with six-window VNIR spectroscopy [13-15].

The Venus facility at PSL is open to the community through the Europlanet Research Infrastructure (http://www.europlanet-2020-ri.eu/).

Venus Emissivity Mapper (VEM): VEM builds on these recent advances in the laboratory. It is the first flight instrument specially designed to focus on mapping the surface of Venus using the atmospheric windows around 1 µm. By observing through all five windows with six narrow band filters, ranging from 0.86 to 1.18 µm, VEM will provide a global map of surface composition as well as redox state of the surface. Continuous observation of Venus' thermal emission will place tight constraints on current day volcanic activity. Eight additional channels measure atmospheric water vapor abundance as well as cloud microphysics and dynamics and will permit accurate correction of atmospheric interference on the surface data.

Conclusion: Interpretation of mineralogy using VNIR spectroscopy data from orbiters [14,15] requires spectral libraries acquired under conditions matching those on the surfaces being studied. Recent advances in high-temperature laboratory spectroscopy at the Planetary Spectroscopy Laboratory at DLR provide the necessary data and enable novel instruments like the Venus Emissvity Mapper.

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CONTRASTS BETWEEN LOW EMISSIVITY TESSERA AND PLAINS MATERIALS ON VENUS MOUNTAINTOPS. M. S. Gilmore, A. J. Stein, and A. Treiman[2], [1]Wesleyan University, 265 Church St., Middletown CT, 06459 USA mgilmore@wesleyan.edu, [2]Lunar and Planetary Institute, Houston TX.

Previous work attempting to model the causes in Magellan 12.6 cm radar properties at high elevations have considered the cumulative emissivity of all surfaces [1-7], without exploring potential differences in the emissivity of geologic units. In this study, we leverage bedrock and impact crater ejecta of known relative age to estimate the rate and style of the weathering reactions at the summits of Ovda and Thetis Regio, which together are the 2nd largest tessera occurrence on Venus. Tessera terrain is a heavily tectonized morphologic unit that comprises 8% of the Venus surface [8]. Tessera terrain is stratigraphically older than the volcanic plains and edifices that cover the remainder of the planet [8]. Surface-atmosphere reactions offer the opportunity to constrain the composition of Venus surface materials, particularly in the highland tessera terrain whose composition is inadequately known [9,10].

Below ~6052 km elevation, all surface units have emissivities of ~ 0.87 (and inferred permittivities of ~2-7), which are consistent with typical rocks and tightly packed soils. Pristine tessera surfaces (Case 4) show a strong decrease in emissivity up to elevations of 6055 km, above which the emissivity increases again monotonically (Figure 1). On the other hand, surfaces mantled with parabola ejecta from the plains (Case 1) maintain essentially a constant emissivity up to the highest elevations. Case 2, tessera surfaces inferred to have been draped with plains ejecta, are intermediate between Cases 4 and 1; they show generally high emissivity (like but somewhat lower than the tessera), and with minima at 6055 km and >6057 km. Case 3, tessera surfaces draped with tessera ejecta, are quite distinct. Case 3 is similar to Case 4, pristine tesserae, up to elevations of ~6054.4 km – a strong monotonic decrease in emissivity. At higher elevations, though Case 3 surfaces show (with some exceptions) even lower emissivity values, down to 0.5 at the highest elevations.

The fact that surfaces draped by visible parabolas (Case 1) do change emissivity with increasing elevation places critical constraints on the timing of the (uncertain) mechanisms that cause surface materials to have low emissivities. The 49 visible parabolas are 10% of the total number of craters on the plains and thus represent ~10% of the average surface age of Venus, or a model age of ~50-100 Ma. If so, then it takes basaltic materials at least 50-100 Ma to undergo the transition to lower emissivities above at 6052 km elevation. Modeled plains parabolas cover the bulk of the Venus surface and yield ages ~ average model crater age of the planet at 0.5 – 1 Ga [18]. In this time frame, basaltic materials may have reacted to form low emissivity materials.

The abrupt drop in emissivity at each of the excursions and return to higher emissivity with increasing altitude supports a model where low emissivity minerals are formed due to a temperature-dependent transition of ferroelectric minerals [2,7]. At or near the Curie-Weiss temperature the dielectric constant increases significantly, followed by a gradual decline in dielectric constant with increasing temperature. We hypothesize that each case under study has different abundances of ferroelectric materials, where ferroelectric minerals are more concentrated in tesserae than in plains materials. Ferroelectric minerals are comprise incompatible elements that are expected to be more common in felsic rocks relative to basalts.

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Measuring spectral properties of candidate minerals: Applications to the Venus radar anomalies

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Radar mapping of the surface of Venus shows areas of high reflectivity (low emissivity) in the Venusian highlands at altitudes between 2.5-4.75 kilometers. The origin of the radar anomalies found in the highlands remains unclear. Previous, and ongoing experimental research investigated possible materials under simulated Venusian atmospheric and surface conditions, with special emphasis on the combined effect of pressure and temperature, and chemical composition. The results of these studies identified candidate source materials for the radar anomalies. In order to fully be considered a true source candidate the material must have spectroscopic measurements comparable to those measured on the surface of Venus where the high temperature affects spectral characteristics of minerals. Spectroscopic measurements of previously identified candidate minerals were made at the Planetary Spectroscopy Laboratory (PSL) of DLR in Berlin in an effort to identify the anomaly source.

The spectroscopic measurements were made with a FTIR Bruker Vertex 80V evacuated to ~.1 mbar and using several pairings of detector+beamsplitter to cover the spectral range from 0.2 to 20 µm. Each sample was poured in a reflectance cup and measured fresh. Successively larger stainless steel cups for emissivity measurements were prepared. Each sample was heated (via an induction system) in vacuum (0.7 mbar) at 400°C for 8 hours, and its emissivity in the VNIR spectral range was measured. Reflectance for each heated sample was measured again in the UV+VIS+MIR spectral range. Three consecutive cycles of heating and measuring emissivity and reflectance were performed to account for spectral variations arising from the thermal processing of the samples.

Results from this study are expected to further constrain the source of the Venus radar anomalies.

The Effects of Venusian Conditions on Galena and Lead

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Introduction: Radar data of the surface of Venus revealed unexpectedly bright regions on some of the highlands [1-3]. Galena (PbS) has been hypothesized as a possible explanation of these bright regions due to its high dielectric constant [4-5]. It is theorized that galena, as well as lead and sulfur, may be released from volcanic activity before being transported to the cooler highlands and condensing on the surface [4]. Galena can also be a source and sink of sulfur on Venus. Although the oxygen fugacity has yet to be constrained [6], galena can oxidize easily, and may transform into a lead oxide and release SO_2 [7]. Though the stability of galena on Venus has been modeled in the past, no experiments have been completed as of yet. Therefore, galena as well as lead are both appealing candidates for the source of the radar bright highlands or as a possible sulfur source and sink on Venus.

Methods: Galena and pure lead powder were tested under Venus conditions using our Venus Simulation Chamber. We took one gram and placed it into the chamber for 24 hours at one of two different temperatures/pressures in one of three different atmospheric compositions. The two tested conditions were 460°C/95 bar (average lowland) and 380°C/45 bar (11 km from surface). The three tested gases were 100% CO_2, 100 ppm of COS in CO_2, and 100 ppm of SO_2 in CO_2. After the completion of each experiment the samples were carefully removed and weighed. The samples were then analyzed with a Panalytical X'Pert MRD to determine if there were any changes in phase or composition.

Results: The control sample had traces of anglesite ($PbSO_4$), therefore all the completed experiments had minute amounts of anglesite in the sample. However, the abundance of anglesite did not appear to alter over the course of the experiment. In the lead experiments completed in CO_2/COS in the highlands, we had a mixture of lead, galena, and $2PbCO_3$-PbO in the sample. In the lead experiments completed in CO_2/SO_2 mixture in the highlands, our sample had lead, galena, 2PbCO3-PbO and shannonite (Pb_2OCO_3).

Discussion: Based on our experiments, when galena is already present, it appears to be stable. Our lead experiments produced galena, which indicates that a reaction is taking place between the lead and the sulfur bearing gases. Our samples also contained either $2PbCO_3$-PbO or $2PbCO_3$-PbO and shannonite. Both compounds have been observed during the thermal decomposition of cerussite ($PbCO_3$). More research needs to be completed to determine if the presence of these compounds is or is not related to the formation of cerussite. If cerussite is being produced in the lead experiments, it is unclear as to why it is not being produced in the galena experiments. Cerussite is stable up to approximately PCO_2 50 bar and 400°C. Therefore, it could be stable on the Venusian highlands, however it is only stable no lower than approximately 10 km from the surface, which is too high to be the source of the radar reflective signal.

Conclusion: Our results indicate that galena does not undergo any observable changes under Venus conditions at both the highland and the lowland. It has not been determined if the galena that formed in the lead experiments exhibit the same level of stability. Longer lead experiments as well as experiments completed in the lowland conditions will be tested in the future. Galena has been discussed as a possible source of the radar reflective signal and a reasonable method of deposition has been discussed in the past. Our results show that lead can react with sulfurous gases found in Venus' atmosphere to produce galena. The high dielectric constant of cerussite makes it a promising candidate for the radar signal, however it would only be stable at the very top of the highlands. However more experiments will need to be completed first to determine if cerussite is forming in the sample.

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Session 03

Evolution (2) Climate

Recent advances in our understanding of Venus climate evolution and remaining mysteries

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It is believed that Venus received similar amounts of volatiles from the proto-planetary nebula as the Earth did. The atmosphere of Venus contains about twice as much carbon and nitrogen as the atmosphere, hydrosphere and sediments of the Earth. The low quantity of water in the present atmosphere of Venus could result from a combination of crustal hydration and past escape processes. The present value of the D/H ratio on Venus, larger than that on Earth by more than a factor of 100, suggests that hydrogen escape has played an important role in removing water from the Venus' atmosphere. Although thermal escape is not sufficient at the present time in removing significant amounts of atmospheric gas, in the form of hydrodynamic escape it could have removed very large amounts of water (the content of one or several terrestrial oceans) during the few first hundred million years. Volatile loss could have also occurred through catastrophic early impacts. These primitive episodes of atmospheric losses, which probably also affected Earth's and Mars' atmosphere, are suggested by noble gas elemental and isotopic data, which remain quite incomplete for Venus. The presence of an early massive atmosphere of water vapor on Venus, which further escaped to space, and/or was trapped in the interior under the form of hydrates, is generally considered to have initiated the strong greenhouse effect observed today. This massive H_2O atmosphere may have been released by the outgassing of the primordial magma ocean. Recent models coupling a cooling magma ocean and a dense atmosphere show that a water ocean might have formed at the surface of Venus at some time in the past depending on the history of cloud formation and initial water content.

I will first summarize the present state of our understanding of the early evolution of Venus' atmosphere. In a second step, I will show how future exploration of Venus could allow to gain a glimpse into the early evolution of Venus and its atmosphere through a necessarily wide exploration program relying on different kinds of probes operated simultaneously, and/or in a step-by-step approach.

The early and long term evolution of Venus and its climate.

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Venus shares some striking similarities with Earth; at the same time, it exhibits characteristics that are widely different from that of our own planet. Indeed, it is an example of an active planet that followed a radically different evolutionary pathway despite the similar mechanisms at work and probably comparable initial conditions. Understanding Venus' evolution might be a key to our comprehension of how a planet can become or cease to be habitable.

We have been developing a coupled numerical simulation of the evolution of Venus, striving to identify and model mechanisms that are important to the behaviour of the planet and its surface conditions. Currently the simulations include modelling of mantle dynamics, core evolution (magnetic field generation), volcanism, atmospheric escape (both hydrodynamic and non-thermal), evolution of atmosphere composition, and evolution of surface conditions (greenhouse effect) and the coupling between interior and atmosphere of the planet. We have also modelled the effects of large meteoritic impacts on long term evolution through three aspects: atmosphere erosion, volatile delivery and mantle dynamics perturbation due to energy deposition.

Volatile fluxes between the different layers of the planet seem critical to estimate how Venus changed over time. This is especially important as we have highlighted the strong role played by mantle/atmosphere coupling in regulating both mantle dynamics and surface conditions through surface temperature evolution. Mantle convection regime evolves with time and depends on surface conditions. We produce scenarios that fit present-day conditions and feature both early mobile lid regime (akin to plate tectonics) as well as late episodic lid regime with resurfacing events. The early history of Venus, in particular, seems to have large repercussions on its long term evolution and present-day state, as it determines volatile inventories and repartition.

Large impacts also affect significantly the evolution of Venus during the Late Veneer era. While the atmosphere erosion they generate is only moderate and doesn't deplete the atmosphere as much as swarms of smaller bodies, they act as a significant source of volatiles. Indeed, if Late Veneer is mainly composed of volatile-rich bodies, it is very difficult to reach the observed present-day state of Venus; instead the atmosphere may become too wet. Large impacts also affect mantle convection, modifying convection patterns for millions of years. Finally, the more energetic collisions (impactors with radii in the 100s of km, high velocity) generate massive melting events near impact location, associated with large scale degassing of the mantle. This leads to mantle depletion and can potentially leave (at least) the upper mantle of the planet dry, with strong consequences for later evolution. Therefore, in the absence of remixing mechanism, large impacts move water from the mantle to the atmosphere and are difficult to reconcile with present-day observation.

Using a modern three-dimensional general circulation coupled atmosphere/ocean model [1] we recently demonstrated [2] that climatic conditions may have permitted liquid water on Venus' surface for ~2 billion years in its early history. Similar such conditions on Earth are believed amenable to the rise of life. Several assumptions were made based on what little data we have for early Venus such as; the type of solar spectrum extant at that time, orbital parameters, estimates of a shallow ocean from Pioneer Venus D/H ratios, and topography from the Magellan Mission. We also assumed that it would have had an atmosphere similar to modern day Earth: 1 bar N2, 400ppmv CO2, 1ppmv CH4. I will discuss the motivations behind these assumptions and additional parameter space studies with direct relevance to hypothetical exoplanetary Venus-like worlds found at the inner edge of the liquid water habitable zone. Finally, I will show how our studies demonstrate that the reason for Venus' present climatic state is unlikely to be related to the gradual warming of our sun over the past 4Gyr as is commonly believed.

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The Evolution of Climate and a Possible Biosphere on Venus

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Of the three local terrestrial planets, two have lost their oceans either to a subsurface cryosphere or to space, and one has had liquid oceans for most of its history. It is likely that planetary desiccation in one form or another is common among extrasolar terrestrial planets near the edges of their habitable zones. As our understanding of terrestrial planet evolution has increased, the importance of water abundance as a substance controlling many evolutionary factors has become increasingly clear. This is true of biological evolution, as wel as geological and climatic evolution. Water is among the most important climatically active atmospheric gasses on the terrestrial planets. It is also a controlling variable for tectonic style and geologic processes, as well as a mediator of surface-atmosphere chemical reactions. Thus, understanding the sources and sinks for surface water and characterizing the longevity of oceans and the magnitude of loss mechanisms on terrestrial planets of differing size, composition and proximity to stars of various stellar types, and the range of physical parameters which facilitates plate tectonics is key to defining stellar habitable zones.

Venus almost surely experienced a transition, early in its history, from a wet, more Earth-like environment to its current hot and highly desiccated state. The timescale is disputed, but recent results using 3D GCM's suggest that, depending on ancient rotation rate and topography, an ancient ocean may have persisted for ~ 2 GY.

A more recent global transition is indicated by the sparse, randomly distributed and relatively pristine crater population, which implies a decrease in volcanic resurfacing rate between 300 and 1000 Myr ago. The accompanying decline in outgassing rate may have caused large climate change. Geological evidence for dramatic changes in resurfacing rate implies large amplitude climate changes which may have left a record of synchronous global deformations and other climatically forced geological signatures. These two transitions may have been causally related if the loss of atmospheric and interior water caused the transition from plate tectonics to single plate behavior.

Today ongoing volcanism most likely provides the ingredients for the global sulfuric acid cloud decks. Rapid loss of SO_2 to carbonates at the surface and H_2O to space strongly implies an active source for these gases on the scale of 10's of MY, a result consistent with surface data suggesting the presence of active volcanism. The stability of Venus' climate is therefore likely dependent upon active volcanism and the sulfur cycle.

For much of solar system history Earth may have had a neighboring planet with life-supporting oceans. During this time the terrestrial planets were not isolated. Rather, due to frequent impact transport, they represented a continuous environment for early microbial life. Life, once established in the early oceans of Venus, may have migrated to the clouds which, on present day Venus, may represent a habitable niche. Though highly acidic, this aqueous environment enjoys moderate temperatures, surroundings far from chemical equilibrium, and potentially useful radiation fluxes. Observations of unusual chemistry in the clouds, puzzling patterns of unidentified solar absorbers, and particle populations that are not well characterized, suggest that this environment must be explored much more fully before biology can be ruled out. A sulfur-based metabolism for cloud-based life on Venus has been proposed. While speculative, these arguments, along with the discovery of terrestrial extremophile organisms that might survive in the Venusian clouds, establish the credibility of astrobiological exploration of Venus.

Variability of the Venusian and Martian nightside ionosphere after solar storms

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1. Introduction

Interactions between planetary atmospheres and the solar wind can be observed via atmospheric emission and ion/electron density profiles. The interaction of the solar wind with Venus and Mars is unique given that both planets lack an intrinsic magnetic field (or, in the case of Mars, only posesses a weak crustal field) and have similar atmospheric composition (95% CO_2).

The Venusian and Martian nightside ionospheres have two distinct electron density peaks: the V1 and V2 peaks for Venus (located near 125 and 150 km), and the M1 and M2 peaks for Mars, (located near 100 and 150 km). These peaks are known to be be highly variable for both planets but the chemical pathways and processes, particularly for the V1 and M1 layers, are not well understood.

Both the V1 and M1 layers exhibit increases in density after intense solar storms, such as coronal mass ejections (CMEs) and solar flares [1, 2]. These increases in density are observed almost immediately and are present on the deep nightside. While ions are transported from the dayside to the nightside of the planet, the time for this process to occur is much longer then the response seen in the electron density profiles. Thus, electron precipitation must play a key role in the variability of these ionospheres. Here, we study the variability of the Venusian and Martian nightside ionosphere and its connection to the solar wind, particularly after solar storms.

2. Observations

Using the Venus Radio Science Experiment (VeRa) instrument on Venus Express (VEX), Mars Radio Science Experiment (MaRS) on Mars Express (MEX), and Langmuir Probe and Waves (LPW) instrument on the Mars Atmosphere Volatile and EvolutioN (MAVEN) spacecraft, we compare electron density profiles of the Venusian and Martian nightside before and after solar storms. Additionally, we compare nightside ion density profiles observed by Neutral Gas and Ion Mass Spectrometer (NGIMS) onboard MAVEN.

3. Discussion

The MAVEN spacecraft is able to observe low ionsphere composition directly. [3] and [4] Giazian et al. 2017 shows that NO^+ is the dominate ion at the M1 level on the Martian nightside. NO^+ was predicted to be the source of the nightside V1 layer on Venus as well as a possible chemical pathway to the observed auroral emission of OI 5577.7 "oxygen green line" [5]. We propose that the the V1 and M1 layers are dominated by NO^+ and that production is sensitive to electron precipitation on Venus.

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Dependence of the H+/O+ flux ratio in the Venusian magnetotail on the solar wind

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Venus has a continuous outflow of H+ and O+ ions from its upper atmosphere through the magnetotail [Futaana et al. 2017]. The ratio of the outflow flux between the H+ and O+ is important to characterise in order to predict the loss of water from Venus' atmosphere through its history. However, the ratio between the H+ and O+ outflowing ions has only been investigated during solar minimum (2006-2009) using Venus Express (VEx) data [e.g. Barabash et al. 2007a, Fedorov et al. 2011]. The ratio was found to be close to 2, which is the stoichiometric ratio of a water molecule. In this study, we extend the analysis of the H+/O+ flux ratio in the magnetotail using all available data from VEx during 2006-2014.

We use the data acquired by the Ion Mass Analyser (IMA), a part of the ASPERA-4 (Analyser of plasma and energetic atoms) instrument package [Barabash et al. 2007b], onboard the VEx spacecraft [Svedhem et al. 2007]. The IMA instrument includes an electrostatic analyser to determine the energy per charge of the measured ions (0.01-15 keV/q) and an assembly of permanent magnets to differentiate the mass per charge of the ion (1 - >40 amu/q). The cylindrical symmetry of the instrument is divided into 16 sectors to determine the incoming direction of ions, and together with the electrostatic deflector, IMA provides a total field-of-view coverage of $\sim 2\pi$ sr. VEx orbited around Venus during 2006-2014, covering both the solar minimum and maximum, which gave in total more than 3000 orbits, making the mission suitable for long term Venus atmospheric escape studies.

We first created average velocity distribution functions of H+ and O+ in the Venusian magnetotail, after the separation of the periods by the solar activity. These average distribution functions are used to calculate the total flux and total escape rates of H+ and O+ through the Venus' magnetotail for different time periods under two different solar activities. Our results indicate that the H+ and O+ fluxes in the Venusian magnetotail is strongly correlated with solar activity. Near solar maximum the total fluxes of H+ and O+ were found to be higher than during solar minimum. The ratio between H+ and O+ also has a strong dependence on the solar activity. In this presentation, we will quantitatively report the escape rate ratio dependence on the solar cycle, and discuss its implications on the history of water at Venus.

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Simulations of ion flow and momentum transfer in the Venus environment

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The solar wind interaction with Venus produces a particularly unique feature. Lundin et al., [2011] using observations from Venus Express (VEX) found the existence of a large-scale vortex-like ion flow pattern in the Venus plasma tail. The flow pattern is characterized by a dominating anti-sunward flow, also a lateral flow component of solar wind (H+) and ionospheric (O+) ions. The lateral flow component is directed opposite to the Venus orbital motion. The combined anti-sunward and lateral H+ and O+ flow wraps over the planetary atmosphere, from the terminator into the nightside. The net lateral flow near Venus is in the direction of the Venus atmospheric super-rotation. Further down in the Venus plasma tail the flow display a circular motion around the central tail axis. This large-scale vortex ion flow pattern has not been observed at other planets or in any simulation of Venus interacting with the solar wind. Lundin et al., [2011] speculated that the observed vortex features are driven by the orbital motion of Venus transverse to the solar wind.

Furthermore Lundin et al., [2011] postulated that the general agreement in direction between the nightside ion flow over the Northern hemisphere, and the retrograde motion of the Venus atmosphere, implies a cause-effect relation between the ionospheric O+ flow and the atmospheric neutral flow. Thus leading them to the question: Is the super-rotating upper atmosphere at Venus a consequence of solar wind forcing? Is the ion flow capable of accelerating, and maintaining, a super-rotating upper atmosphere at Venus?

In this presentation the hypothesis of Lundin et al., that the orbital motion of Venus transverse to the solar wind flow drives the ion tail vortex and potentially the super-rotation up the upper atmosphere is tested. We perform hybrid (kinetic ion, fluid electron) simulations of the Venus solar wind interaction using the HALFSHEL code. The simulations include models for the ionospheric chemistry, ion-neutral collisions, Hall and Pederson conductivities. The model atmosphere (densities and dynamics) used in the simulations are taken from the VTGCM code. The orbital motion of the planet is included in the simulations by moving the planet each time step. The Venusian ion tail is examined to check for the ion vortex. Furthermore, we examine the magnitude and location of the energy and momentum deposited into the neutral atmosphere by the solar wind and pickup ions to examine the postulate that ion flow is capable of accelerating and maintaining the super-rotation in the upper atmosphere of Venus.

Session 04

Aeronomy and Plasma Environment

Upper atmosphere of Venus and impact from solar wind plasma: What we have learnt from Venus Express?

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Abstract

Venus is nicknamed "Earth's twin" due to the similarities in size, gravity, and distance from the Sun. However, Venusian atmosphere is completely different from the terrestrial atmosphere in terms of the pressure, composition, and so on. From a space plasma point of view, the most significant difference the lack of the dipole magnetic field at Venus. The lack of dipole indicates that the upper atmosphere and ionosphere interact with the solar wind plasma directly. This means that the solar wind plasma momentum and energy are injected into the upper atmosphere. It has been discussed the momentum and energy inputs from the solar wind are one of the key physical mechanisms to erode the upper atmospheric composition. The main component of interest has been water molecules. Such a loss of the water molecules at Venus over billion year scale is thought to be consistent to the high D/H ratio at Venus compared to that at the Earth.

In 2006, Venus Express (VEX) was inserted into a Venusian orbit. One of the scientific objectives of the VEX mission is to investigate the solar wind interaction in a context of the "fate of water". For this purpose, VEX equipped with the magnetometer (MAG) and the plasma and energetic neutral atom (ENA) package (ASPERA-4). The VEX mission was operated for 8.5 years, and completed its mission in 2014. During the mission, MAG and ASPERA-4 were operated, and these instruments provided a large amount of datasets.

VEX measured plasma environment in the polar, terminator and magnetotail regions of Venus. The ionosphere to near-tail regions host dynamic processes that lead to plasma energization, leading to the loss of ionospheric ions to space with their composition rate of H^+ and O^+ as 2 to 1. It indicates that the water molecules are escaping now through the magnetotail due to the solar wind interaction (while lighter H^+ could escape through other pathways). VEX plasma measurements also have revealed responses of the structure and dynamics of the Venusian induced magnetosphere to the prevailing solar wind conditions with various time scales. We review what has been found by VEX in a context of the interaction between the upper atmosphere and the solar wind. We further will formulate the key open questions to extend our understandings about Venus for future missions; and more in general, to extend our understandings about other Solar System bodies and exoplanets.

The Venus Ionosphere as seen by the Akatsuki Radio Science Experiment

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The radio science experiment on the japanese Venus orbiter Akatsuki is sounding the ionosphere of Venus in the one-way radio link mode at X-band (8.4 GHz). The radio link is stabilized by an on board Ultrastable Oscillator (USO). Because of the geometry of the Earth/Venus/Akatsuki constellation, Earth occultations occur in seasons. Akatsuki will have finished its third season at the time of this conference. The locations of the occultation ingress and egress positions during a season are confined in a band within the mid-latitudes on both hemispheres. Ingress and egress local times are at night to early morning and afternoon to early night, respectively. This work will present the ionospheric electron density profiles from the first seasons of Akatsuki radio sounding and will compare those directly with VEX-VeRa ionospheric electron density profiles at similar locations, local times and solar zenith angles but from different phases of the solar cycle.

Understanding the impact of waves on Venus' Upper Atmosphere through General Circulation Model Simulations

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The upper atmosphere of Venus has been observed for many decades by multiple means of observations (e.g., ground-based, orbiters, probes, fly-by missions). The European Space Agency Venus Express (VEX) orbiter and more recently the Japanese mission, Akatsuki, have been providing illuminating observations of the Venusian atmosphere. From past and present observations there is evidence of wave activity contributing to Venus' atmospheric dynamics and variability. Systematic studies with theoretical models can help better understand the underlying physical processes.

The Venus Thermospheric General Circulation Model ((VTGCM), e.g. Brecht et al., 2011) has improved upon the already existing constraints by including more chemistry (OH nightglow, SOx, $[SO]_2$), modern energy budget calculations (near-IR and aerosol heating, NLTE 15-μm cooling), and wave specification and parameterizations (planetary-scale waves and small scale gravity waves).

The presented work will focus on VTGCM simulations and their comparisons with published observations in regards to wave-induced variability within the circulation and nightglow emissions. Small-scale gravity waves, incorporated into VTGCM by a whole atmosphere gravity wave parameterization (Yiğit et al., 2008), along with specified internal waves (Kelvin and Rossby waves) impact the background atmosphere. The effects of these subgrid-scale waves and large-scale internal waves on atmospheric circulation will be discussed. The O_2 IR nightglow emission and the NO UV nightglow emission are great features to observe and help constrain circulation. The location (spatial and temporal), intensity, and variability of these emissions provide information (model constraints) on temperature, winds, and density. These emissions have been observed and their averaged behavior has been documented (Soret et al., 2012; Steipen et al., 2013). However, the emission variability (and the wave processes responsible) has not been studied in detail. The impacts the wave specification and parameterizations have on these emissions and their variability will also be presented.

The Impact of Venus Middle Atmosphere Energy Balances upon Dayside Thermosphere Temperature and CO Density Distributions through GCM Model Simulations

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Introduction and Motivation. One of the major goals of the Venus Express (VEx) mission has focused upon increasing our understanding of the highly variable global circulation and wave processes impacting the Venus mesosphere-thermosphere (~80 – 200 km). Several VEx instruments (e.g. SOIR, SPICAV and VIRTIS) and ground based observations have provided measurements that characterize the upper atmosphere structure and underlying variable dynamics during the solar minimum-to-moderate period of the solar cycle when VEx measurements were obtained (2006-2014). For example, VIRTIS-H profiles of dayside temperatures and CO densities have been obtained and analyzed [1]. These datasets were used to establish a statistically averaged mean state (versus latitude) and characterize the variability of the upper mesosphere and lower thermosphere structure. Our overall goal is to examine this spatial and temporal variability about the mean, thereby providing constraints for the VTGCM mean thermospheric winds and CO distributions (plus variable planetary and tidal wave driven features) [2, 3].

Venus Express Measurements and Usage. A detailed study of the VEx/VIRTIS-H measurements of the limb emission of CO in the 4.7-micron spectral region has been carried out [1]. A comprehensive NLTE treatment of the emissions was implemented, enabling retrievals of dayside CO densities and temperatures (T) over ~100-150 km. These retrievals are noisy, but can be improved with suitable averaging of datasets. These T retrievals are consistent with the recent compilation of VEx and ground based measurements of dayside temperatures [4]. We review these existing VIRTIS-H dayside measurements that provide constraints on T and CO densities, as well as the changing global circulation patterns and wave processes. We also provide a re-analysis of data-VTGCM comparisons of dayside T and CO density profiles as a function of latitude and altitude (~100-150 km). The underlying VTGCM processes maintaining the observed mean T and CO density distributions are quantified and discussed. Implications for variable global winds (especially the subsolar-to-antisolar component) are also examined.

VTGCM Modeling. The Venus Thermospheric General Circulation Model (VTGCM) has been recently improved [2, 3] by including new chemistry (OH nightglow, SOx, $[SO]_2$), modern heating and cooling formulations (near-IR and aerosol heating, NLTE 15-μm cooling), and wave parameterizations (planetary-scale waves and small scale gravity waves). For this study, the heat balance upgrades below ~100 km are shown to be important, owing to their impact upon lower thermosphere CO densities for comparison to VIRTIS-H datasets. Other conference presentations will focus upon VTGCM studies that address: (a) OH nightglow as a tracer of the upper atmosphere global circulation [5], and (b) gravity wave and planetary wave impacts on the Venus thermosphere [3].

References: [1] Gilli et al., (2015); Icarus, 248. [2] Brecht and Bougher (2012); JGR, 117. [3] Brecht et al. (2018); this conference. [4] Limaye et al. (2017); Icarus, 294. [5] Parkinson et al. (2018); this conference.

Circulation of Venusian atmosphere at 90-110 km based on apparent motions of the O_2 1.27 µm nightglow from VIRTIS-M (Venus Express) data

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In the atmosphere of Venus at 90-110 km altitudes in the transition region between the superrotation and the subsolar-antisolar circulation, tracking of the $O_2(a^1\Delta_g)$ 1.27µm nightglow is practically the only method of studying the dynamics. The nightglow images were obtained by VIRTIS-M on Venus Express from 2006 to 2008. The horizontal wind speed can be obtained by tracking the displacement of the bright morphological features at given pairs of images. The resulting global mean velocity vector field covers the nightside between latitudes 75°S – 0°N and local time 19 h – 5 h. The mean zonal and meridional components are asymmetrical between the morning and the evening side in terms of direction and magnitude. The zonal wind speed in the eastward direction from the morning side exceeds the westward (evening) by 20-30 m/s, and the streams “meet” at 22±1 h. The meridional component is predominantly poleward on the morning side, ranging from 0 to -50 m/s, and changes to equatorward at mid-latitudes. The influence of underlying topography was suggested in some cases: above mountainous regions flows behave as if they encounter an "obstacle" and "wrap around" highlands. Instances of circular motion were discovered, encompassing areas of 500-4000 km.

Search for lightning discharge in Venus with Akatsuki/LAC and Pirka telescope

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The existence of lightning discharge in Venus has been controversial for three decades, which might be attributed to the luck of conclusive observational evidence. There had been no satellite payload intentionally designed for the detection of lightning phenomena using radio wave or optical sensor. LAC, lightning and airglow camera, on board Akatsuki spacecraft, is the first sensor optimized for the lightning optical flash measurement in planets other than the Earth. It is expected that LAC could conclude this 30-year discussion on the existence of lightning in Venus. Unique performance of LAC compared to other equipment used in the previous exploration of Venus is the high-speed sampling rate at 20 kHz with 32 pixels of Avalanche Photo Diode (APD) matrix, enabling us to distinguish the natural optical lightning flash from other pulsing noises, including artificial electrical noise and cosmic rays. We selected OI 777 nm line for lightning detection, which is expected to be the most prominent emission in CO2-dominant atmosphere based on the laboratory experiments.

The regular operation of LAC for lightning hunt was started on December 1, 2016. Due to the elongated orbit than that planned originally, we have an umbra for approximately 30 min to observe the lightning flash in the night side of Venus every 10 days, which is almost 1/20 rate of the original plan. The triggering parameter was set so as to optimize for the light curve similar to the normal lightning in the Earth and data obtained totally for about 4 hours were examined. However, we couldn’t find any lightning signals. Adding to this triggering parameter set, we added one more parameter set, optimized for sprite type emission with duration of up to 10s of ms. These two sets are in rotation at every 60 sec. Furthermore, in order to investigate fainter emissions, we are now conducting successive force triggering recordings without any threshold, achieving 5 times better sensitivity than the intensity of 1 digital unit at best. Here we report the detailed strategy and the latest status of the LAC observation after the winter-spring campaign in 2018, and discuss the possible explanation for the occurrence rate estimated by all LAC observations.

Also we will make ground observation with a high-speed photometer installed at Pirka telescope, a 1.6-m reflector deployed by Hokkaido University. Here we report the initial results of lightning flash observation with it.

Statistics of Poynting Flux from Lightning Generated Whistlers at Venus

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The existence of lightning on Venus has been studied by numerous space missions for over 50 years. The Soviet Venera landers detected radio waves due to lightning during the descent of the landers and while on the surface. Venera 9 even detected an optical signature with its visible spectrometer. The Pioneer Venus (PVO) orbiter also detected radio waves determined to be from lightning, but only while on the nightside because of excessive noise in the electric antenna caused by the sun. These signals exhibited a decrease in amplitude at higher altitudes, implying a source from below, i.e. lightning in the clouds. Most recently, Venus Express (VEX) detected whistler-mode waves in the Venus ionosphere with its dual fluxgate magnetometer. The entire 8.5+ year dataset has been analyzed with nearly 10 hours of whistler activity identified. Signal lengths range from one second to more than one minute. The majority of the signals were detected when VEX was around 250 km, approximately 4% of the time it was near this altitude.

In order to demonstrate that the whistlers detected by VEX originate below the ionosphere we first need to calculate the Poynting vector, which is difficult for two reasons: VEX had no electric field sensor and it did not take measurements of the electron density in the lower ionosphere where these signals were observed. Thus, we have employed the VIRA electron density model, which allows us to estimate the Poynting flux of the waves. Since the model was developed during the PVO era, when the solar EUV was more intense, we have scaled it to match the solar cycle conditions during the VEX campaign. With the three components of the magnetic field and an estimate of the electron density, we can statistically show that the whistler-mode waves observed by Venus express do indeed originate from the atmosphere below. Next, we estimate the energy of the bursts and compare Venus lightning rates to terrestrial lightning and rates.

Session 05

Clouds and Chemistry

Spectroscopy of Venus in the near UV: SO_2, clouds and O_3

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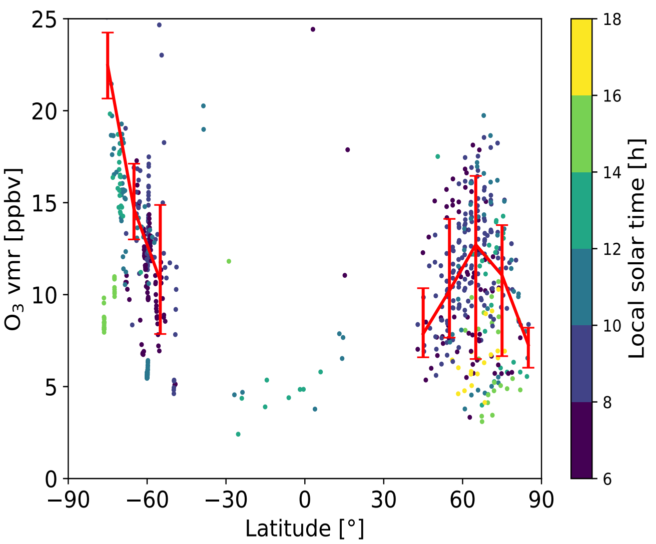
SPICAV [Bertaux et al., 2007] was a UV and IR spectrometer on board Venus Express, ESA's first mission in orbit around Venus (2006−2014). Observations of the reflected UV sunlight (170 to 320 nm, R ∼ 200) by SPICAV during the whole mission were sensitive to many variable quantities near Venus' day side cloud top (65 − 75 km): gaseous constituents such as SO_2 [Marcq et al., 2011, 2013] and O_3, UV absorption caused by a yet unknown UV absorber within submicron particles, cloud top altitude (via CO_2 absorption).

Here we present the first full analysis of the complete SPICAV-UV nadir data set. First findings include: (i) detection of ∼ 10 ppb cloud top O_3 at latitudes higher than 50° [Marcq et al., in prep.] (ii) confirmation of most of the spatial and temporal trends of SO_2 climatology as described by Marcq et al. (2013, 2011) and other observers [Jessup et al., 2015 ; Encrenaz et al., 2012, 2013, 2016]: short-lived bursts of SO_2 at lower latitudes, happening more often in the 2006-2009 epoch (iii) spatial and temporal variations of the UV absorber embedded in mode 1 particles, with darker lower latitudes and a possible secular darkening.



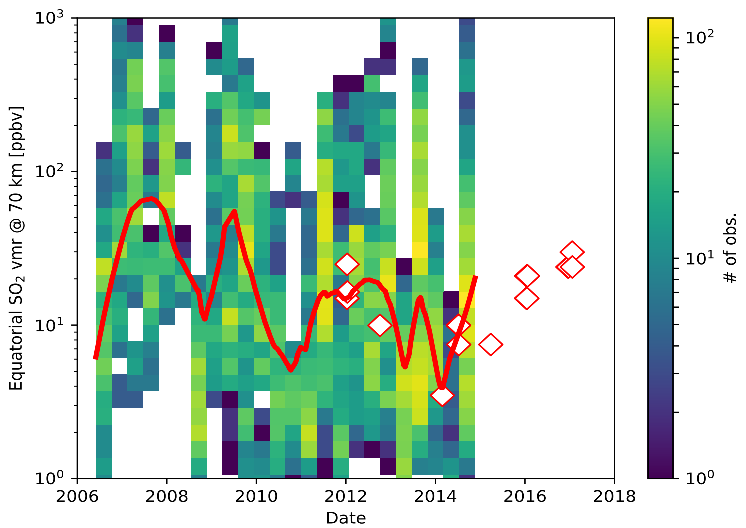


Fig. 1 (left) *cloud top (55-70 km) O_3 measurements in 2006-2014 using SPICAV/Venus Express*
Fig. 2 (right) *Moving median (solid red) SO_2 mixing ratio as measured by SPICAV/Venus Express, and TEXES measurements from Encrenaz et al. (white diamonds).*

Investigation of high-altitude aerosols of Venus with Akatsuki/IR2 2.02-μm images at large phase angles

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IR2 onboard Akatsuki recorded 2.02-μm dayside images at a variety of solar illumination conditions (phase angles). Images at large phase angles (> 120°) are expected to carry wealth of information about physical property of upper aerosols as well as their spatial distribution. Unfortunately, the solar heating to the spacecraft at large phase angles are too severe to the IR2 cooling system, causing unfavorably high detector temperature. In addition, strong brightness surge of Venus dayside at large phase angles saturated the detector pixels in majority of such images.

To overcome this problem, we have developed an algorithm to estimate the *true* brightness of dayside disk in saturated images. As reported by Satoh et al. (2017), multiple reflection of infrared light in the IR2 detector causes elongated tail of the point-spread function (PSF). Therefore, the light spread over the "deep space" pixels may potentially retain the information about the true brightness of dayside disk. Our algorithm includes the following steps: (1) a synthetic dayside disk is created (Minnaert's law with a coefficient k); (2) the disk image is convolved with the IR2 PSF; (3) convolved disk image is brightened by a factor F; (4) the resultant synthetic image is overlaid on observed image; (5) deconvolution is performed on the image; and (6) iterated (k and F are modified) until reasonably flat "deep space" pixels near the Venus disk is achieved.

With the above method, we have analyzed IR2 2.02-μm images acquired in Orbit 29 (October 2016). The phase angles are 143-145° (Oct 11), 138- 140° (Oct 12), 134-136° (Oct 13), 129-131° (Oct 14), 125-127° (Oct 15), and 120-122° (Oct 16). These will make a good extension to a phase curve, up to 120°, reported by T. M. Sato. It is found that a Minnaert coefficient of k=0.70 seems to work reasonably well for this phase angle range. Estimated values of the brightness factor F are 28.0 (143-145° phase angle), 18.0 (138-140°), 15.0 (134-136°), 13.0 (129-131°), 10.0 (125-127°), and 7.5 (120-122°).

In addition to the disk photometry, we also studied the "close-up" limb image captured while the spacecraft was travelling near the pericenter on 30 October 2016. A high-resolution limb image was acquired at 03:09:42 UT from a distance of 8239 km (to the planet center). The phase angle range in this image is 121-133° and a detached high-altitude haze layer is detected in this "forward scattering" condition. Reflected sunlight from the main cloud deck is so intense that the pixels are saturated. We therefore modeled the dayside disk with the above method to measure the intensity of light scattered from the detached haze.

Results of radiative transfer analysis of these data will be presented and physical interpretation will be discussed.

Mapping of Venus' cloud top altitude from Akatsuki/IR2 dayside images

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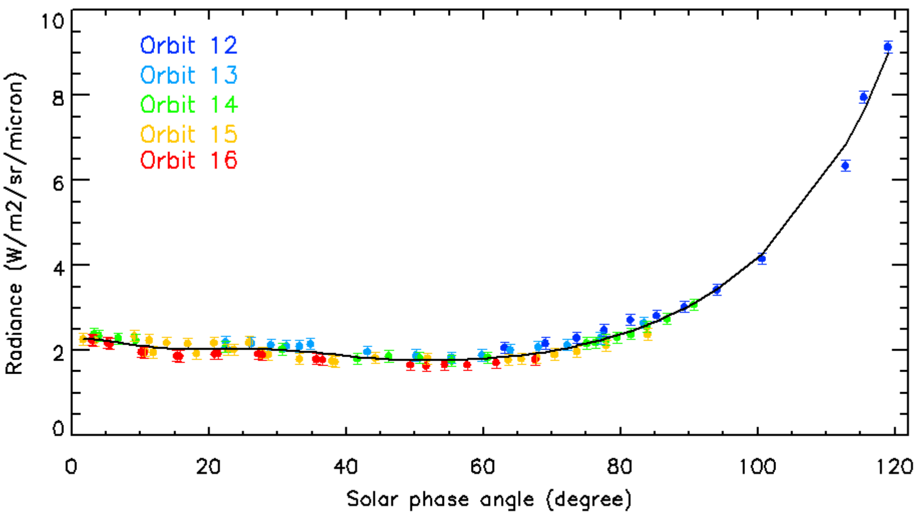
We have analyzed a total of 93 Venus' dayside images taken by the 2.02-μm channel of 2-μm Camera (IR2) onboard Japanese Venus orbiter, Akatsuki, during the period from April 4 to May 25, 2016 (Orbits 12-16), for the purpose of mapping cloud top altitude. Since the 2.02-μm channel locates in a CO_2 absorption band, the observed brightness contrast is interpreted as resulting from the difference of the optical path length to the cloud top: the cloud top altitude can be retrieved by reproducing the observed radiance with radiative transfer calculation. We first investigated the observed phase curve (solar phase angle dependence of the radiance) for the equatorial region to constrain the averaged cloud top structure characterized by cloud top altitude (z_c), cloud modal radius (Mode 2, $r_{g,2}$), and cloud scale height (H). The best-fit model is obtained at the combination of z_c=70.3 km, $r_{g,2}$=1.25 μm, and H=6.5 km and its simulated phase curve is compared with the observed one shown in the figure below. Although the obtained cloud modal radius and cloud scale height are somewhat larger than the previous studies with Venus Express data, the cloud top altitude is found to be compatible. We retrieve cloud top altitude maps under the assumptions that the pixel-to-pixel radiance variation arises as the deviation from the averaged cloud top structure and can be explained by the change of the cloud top altitude while keeping the other parameters unchanged.



Title:
Intense Decadal Variation of Venus' UV Albedo and its Impacts on the Atmosphere

Authors:
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Abstract:

Around 70 km altitude from the surface, Venus' an unidentified absorber creates broad absorption spectrum in the UV-to-visible wavelength range that peaks around 340-380 nm. Recent efforts to identify this unknown absorber suggest several candidates, e.g., OSSO, S_2O, S_x, $FeCl_3$, by fitting observed spectra or through chemical modeling. However, the chemical composition of this absorber is yet an unsolved question, and even iron-bearing microorganism has been suggested. Regardless on its identity, it is known that it absorbs about half of the solar energy deposited in the atmosphere according to several model calculations. As a result, the unidentified absorber plays a critical role in the atmospheric energy balance.

Here we report the first quantitative study on the variability of the cloud albedo at 365 nm and its impact on Venus' solar heating rates based on an analysis of Venus Express (2006-2014) and Akatsuki (December 2015-May 2017) UV images, and MESSENGER (June 2007) and Hubble Space Telescope (January 2011) UV spectral data. These results show that the 365-nm albedo varied by a factor of 2 from 2006 to 2017 at both high and low latitudes. This is the largest level of decadal variations compared to the other bodies in the Solar System.

We take into account this observed range of 365-nm albedo variations in our radiative transfer calculations, fitting the observed albedo by multiplying factors to the mode-1's assumed absorption coefficient for the unknown absorber in the spectral range of 310-780 nm (Crisp 1986). The results show that the observed albedo variance can produce a -25~+36% variance in the low latitudinal local noon time solar heating rate. This means that the cloud top level atmosphere should have experienced considerable solar heating variations over a decade.

We suggest that this variable solar heating would drive dynamical changes like the reported Venus' zonal wind variations from 2006 to 2017. The solar heating rate variances may also provide the first evidence of climate change on Venus due to the clouds, a phenomenon distinct from other terrestrial clouds which buffer against climate change.

Glory as an effective tool for retrieving the properties of the Venus upper clouds from the VMC/VEx data

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Physical processes in the Venus clouds are driven by the solar radiation energy mainly absorbed in the upper cloud layer. Knowledge of the sizes and nature of aerosol particles composing the clouds is required for studying the radiative energy balance of the planet. During 2006 – 2014 the Venus Monitoring Camera (VMC) onboard Venus Express (VEx) was imaging the Venus clouds in four narrow spectral channels (0.365, 0.513, 0.965 and 1.01 μm) that shared one CCD and took around 350 000 images covering almost all the latitudes, including night and day sides. Observations of glory, an optical phenomenon observed near opposition, turned out to be of key importance for retrieving the optical properties of Venus upper clouds, since it poses constraints on the properties of cloud particles: they have to be spherical, and their size distribution has to be narrow [1]. The angular positions of glory features (maximum and minimum) are determined by the size of particles, and the brightness enhancement at opposition is sensitive to their refractive index in near-infrared for the considered size range. The first images of a full glory in unpolarized light on the upper cloud deck of Venus were obtained with VMC [1] (fig. 1a). From fitting the phase profiles of brightness with the radiative-transfer models the optical properties of clouds and their spatial (in latitude) and temporal (in local time) variations were obtained [1–3].

It was found that the cases with a relatively high real part of the refractive index of aerosols are often observed (especially at low latitudes) for the 1-μm mode of cloud particles: 1.45 – 1.49 (with sporadic spikes up to 1.52) instead of a widely used value of 1.44, which is characteristic of the 75 % sulfuric acid solution (fig. 1d). This suggests that an additional component with a high refractive index, like sulfur or ferric chloride, should be present in the cloud droplets serving as condensation nuclei for sulfuric acid. Both these materials are often proposed as candidates for the as yet unknown UV absorber, which is responsible for the UV contrasts observed in clouds. When analysing the full near-IR data set of VMC, we also found that the sizes of the 1-μm mode in the upper clouds decrease at high latitudes, and the amount of submicron particles within the clouds and the overcloud haze increases in the morning and at high latitudes [2, 3].

The clouds of Venus scatter radiation in the visible and near-IR wavelengths nearly conservatively, and the contrasts between the planetary disk details do not exceed 2 – 4 %. However, many features are observed in UV, where the contrast, which is partly caused by SO_2 (between 0.20 and 0.32 μm) and partly by the unknown UV absorber (at ∼ 0.365 μm), reaches 20 – 30 %. Observations of glory was successfully used to study the causes of the contrast appearance in the clouds [4–6]. For example, it was found that variations in the composition of submicron particles, composing the clouds together with the 1-μm mode, play a key role in the UV contrasts observed at low latitudes near the local noon [4]. Since the glory feature is always observed on the cloud top of Venus, the property of composite H_2SO_4 particles with embedded or adhered impurity grains to produce the glory feature makes it possible to select between the UV-absorber candidates wetted or non-wetted by H_2SO_4; it was shown that sulfur can hardly be responsible for the UV contrasts, because it is not wetted by H_2SO_4 [7].

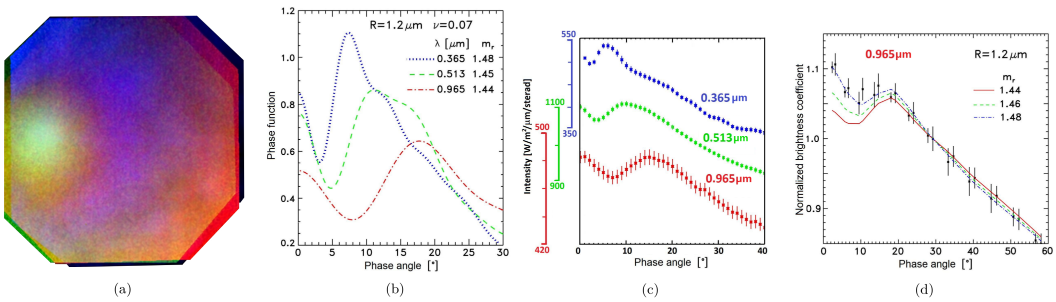

Figure 1: Venus glory as observed by VMC: (a) a false-color composite image; (b) an example of the single-scattering phase functions for the VMC wavelengths; (c) an example of the observed glory profiles; (d) the normalized measured values of near-IR brightness as a function of the phase angle are compared to the models (lines) with different refractive indices m_r.

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Correlation of Cloud Morphology at the Venus' Cloud Top between different wavelengths studied with Akatsuki observations

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We investigated the spatial distribution of the correlation between Venus' cloud images taken at different wavelengths by the Venus orbiter Akatsuki.

We preprocessed images as follows. We used the Level-3 data product in which images have been projected onto the latitude-longitude coordinates. Firstly, a pair of Venus images taken almost simultaneously at different wavelengths are prepared, and the large-scale brightness variation due to the change of the incidence and emission angles over the Venus disk was removed by using Minnaert law (except for thermal infrared 10 μm (LIR) images). Then these images are processed by high-pass filtering by subtracting a Gaussian-smoothed image from each original image. This filtering with the variable width of the smoothing function enables us to compare cloud features at various scales.

The procedure of the correlation coefficient mapping is as follows. Firstly, we set square regions, with sizes twice the half width of the Gaussian filter used in the preprocessing, in the pair of images at the same geographical location. Then the correlation coefficient between them is calculated and plotted on the geographic location corresponding to the center of the square region. This procedure is repeated while sequentially shifting the square region pixel by pixel over the whole image area to create a correlation coefficient map.

As the size of the square region for which the cross-correlation is calculated, three different values of 4°, 6° and 8° both in latitude and longitude are examined. Firstly, strong positive correlation (around +0.8) is dominant between the ultraviolet channel of 283 nm and 365 nm(UVI) for all spatial scales. Since 283 nm corresponds to the absorption by SO_2 and 365 nm reflects that of the unknown UV absorber, it indicates the unknown UV absorber may have some relationship with the Venus' sulfuric cycle. The dayside near-infrared 2.02 μm (IR2) and the thermal infrared 10 μm (LIR) are negatively correlated (around -0.3) in most of the cases, which suggests an inverse relationship between the cloud height (shown in IR2) and the cloud top temperature (seen in LIR). The dayside 2.02 μm (IR2) shows strong negative correlation (around -0.6) with 283 nm and 365 nm (UVI). This result may indicate these UV absorbers get abundant when the clouds get higher. We will also discuss the latitudinal dependence of the correlation mentioned above.

Laboratory investigation of Venus aerosol analogs

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Abstract:
The Venusian cloud deck is a 20-km-thick global layer of micron-scale sulfuric acid droplets with other trace components. This cloud layer absorbs fully half the incident solar radiation and is important for understanding the thermal balance, composition, and chemistry of the Venusian atmosphere [1,2]. Absorption of solar radiation in the cloud deck creates mesoscale convective cells near the subsolar point [3], drives overturning circulation [4], and maintains the global atmospheric superrotation [4,5]. A complex sulfur cycle sustains the extensive cloud layer, which includes particles of sulfuric acid, elemental sulfur, and an unidentified ultraviolet absorbing species [3]. A basic knowledge of the composition and morphology of Venusian aerosol has existed since the 1970s. Nevertheless, several major questions persist: what is the nature of UV-absorptive species at the cloud tops? Do large particles exist in the clouds? What is the composition of the non-sulfuric-acid component of the clouds? What are the properties of the (non-cloud) haze layers and how do they form?

To date, no laboratory investigations of Venusian aerosol formation have been performed, even with these longstanding questions. We have designed a series of experiments to investigate these questions. We expose simulated Venusian atmospheres composed of CO_2 and SO_2 (with SO_2 mixing ratios ranging from parts-per-million to several percent) to an energy source to initiate photochemical reactions in the laboratory. These new experiments are based on a large body of work regarding the production of organic haze particles in the atmosphere of Titan (see [6] for review). Laboratory experiments of sulfate aerosol formation have been performed with Earth-like atmospheres [7,8], but similar investigations have not yet been performed for strongly oxidized Venus-like atmospheres.

Preliminary experiments performed with Venus-like gas mixtures of SO_2 and CO_2 exposed to plasma discharge or UV radiation generate micron to millimeter size particles. We plan to analyze these particles by mass spectrometry, scanning and transmission electron microscopy, and infrared (FTIR) spectroscopy to determine composition. FTIR and UV-VIS spectroscopy (0.175 – 29 μm) will be used to determine how the particles interact with light and will allow for comparisons to recent spacecraft observations, e.g. [9–11].

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Session 07

Atmospheric Dynamics(1)

Investigations below the clouds of Venus with the IPSL Venus GCM.

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Thanks to the various space missions that investigated Venus's atmosphere since the 70's, and in particular the recent Venus-Express (Europe, 2006-2014) and Akatsuki (Japan, 2015-) missions, the atmosphere of Venus above roughly 45 km altitude including the clouds (~48-70 km) has been thoroughly investigated. This vast amount of data helps to understand how this complex atmospheric system works, in particular with the help of advanced Global Climate Models (GCMs). However, data from below the clouds are sparse, despite the importance of the deep atmosphere in the global behavior of Venus's atmospheric system: peak of angular momentum content, interactions between surface and atmosphere (including angular momentum exchange, volcanism, weathering). A better knowledge of the region is also needed for specific mission planning purposes, such as aerial platforms or landers. To investigate this region while planning new missions, GCMs are valuable tools and we review here all the studies conducted on this region with the IPSL Venus GCM developed in Paris (Lebonnois et al., 2016; Garate-Lopez et al., 2018).

To model the temperature profile in the deep atmosphere, it is crucial to investigate the radiative transfer and the opacity sources below the clouds. Lebonnois et al. (2015) studied how the solar energy absorbed below the cloud may be balanced with infrared energy heating the base of the cloud, convecting up to the middle cloud to escape finally to space mostly in the 20-30 micron region. Using recent solar flux calculations (Haus et al., 2015) and up-to-date datasets for IR gaseous opacities and collision-induced absorptions, the temperature profile in our GCM is tuned through assumptions on the haze below the cloud to fit the observed temperature profile between the cloud base and the surface.

Though we obtain realistic superrotation in the upper cloud, the vertical profile of zonal wind observed below 60 km is not fully understood. Around the cloud base (40-60 km), wave activity obtained in our most recent simulations contributes to angular momentum convergence in the equatorial region (Garate-Lopez et al., 2018). In previous simulations (Lebonnois et al., 2016), large-scale gravity waves were transporting angular momentum equatorward and downward, improving the distribution of zonal wind below 40 km. As both wave activities are not obtained in the same simulations, we are investigating the conditions for the development of each of these wave groups and will detail our most recent conclusions in this talk.

Near the surface, the IPSL Venus GCM was also used to investigate the behavior of the Planetary Boundary Layer (PBL), in particular diurnal convective activity (Lebonnois et al., submitted). The deepest 10 km above the surface are neutrally stable in our simulations, a peculiar environment for the diurnal cycle of the PBL. A nocturnal stable layer is obtained due to cooling of the surface during nighttime. In daylight hours, convection develops in mid- to low-latitude regions, with a maximum around noon and a convective layer mostly limited to just over 1 km thickness. Strong slope winds are obtained in the simulations, with a diurnal cycle: downslope katabatic winds at night, upslope anabatic winds during daytime. The convergence of anabatic winds at noon over the western slopes of topographic features induces a large increase in the vertical extension of the convective activity, reaching higher than 5 km thickness in some of these regions.

The interactions between the near-surface flow and the topography are also explored with the IPSL Venus GCM (Navarro et al., 2018). A parameterisation of the drag due to orographic gravity waves generated by topographic features is now implemented and can help interpret the stationary bow-shape waves observed at cloud-top by the Akatsuki spacecraft.

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Acknowledgements

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Numerical modeling of the Venus atmosphere

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It has been revealed by recent space-craft and ground-based observations that various atmospheric activities such as thermal tides, polar vortex, and Kelvin- and Rossby-type waves occur in the Venus atmospheric superrotation in the cloud layer. In order to elucidate generation mechanisms of these activities and their dynamical effects on the superrotation, we have developed a general circulation model (GCM) for the Venus atmosphere named AFES-Venus, which is based on AFES (AGCM for Earth Simulator) (Ohfuchi et al., 2004; Enomoto et al., 2008). Recently, AFES-Venus has been extended for the data-assimilation (Sugimoto et al., 2017).

Results we have obtained so far are summarized as follows:

- Superrotating winds consistent with the observations (e.g., Machado et al., 2017) have been reproduced in the AFES-Venus simulations.
- Baroclinic instability appears in mid-latitudes in the cloud layer (Sugimoto et al., 2014a; 2014b). The Rossby waves and the Y-shape pattern observed at the cloud top might be explained by the baroclinic instability waves.
- A cold band encircling the warm polar region called "cold collar" is attribute to the residual mean meridional circulation enhanced by the thermal tide (Ando et al., 2016).
- Vertical temperature structures and their temporal variations in the polar atmosphere observed by radio occultation measurements are interpreted as neutral barotropic Rossby waves related to barotropic instability in the polar region (Ando et al., 2017).
- Three-dimensional structures of the thermal tide indicate a strong circulation between the subsolar and antisolar (SS-AS) points in the cloud layer superposed on the superrotation (Takagi et al., 2018). The SS-AS circulation can contribute to the material transport, and its upward motion might be related to UV dark clouds observed near the subsolar region in low latitudes.
- Streak features of the lower cloud observed in night side images of Akatsuki IR2 camera, reproduced for the first time, are related to baroclinic instability in the cloud layer (Kashimura et al., submitted).

At the conference, we will discuss some more recent results including short-period disturbances and topographic waves.

Planetary-scale streak structures reproduced in a high-resolution simulation of Venus atmosphere

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Introduction

Night-side images of Venus taken by the IR2 camera on board the Venus Climate Orbiter/Akatsuki has shown many features of the lower cloud layer. One prominent feature is a bright planetary-scale streak structure extending from high-latitudes to low latitudes on both hemispheres. Because the IR2 night-side images capture infrared radiated from the near-surface atmosphere, the bright regions indicate thin-cloud regions.

Numerical model and set up

We have performed a high-resolution simulation of the Venus atmosphere by a simplified general circulation model, which is based on AFES: the Atmospheric general circulation model For the Earth Simulator. The horizontal resolution is T159 (i.e., about 0.75 deg x 0.75 deg grids) and the vertical resolution is about 1 km with the model top at 120 km. In the model, the atmosphere is dry and simply forced by the solar heating with the diurnal change and Newtonian cooling that relaxes the temperature to the horizontally uniform basic temperature which has a virtual static stability of the Venus atmosphere with a low-stability (0.1 K/km) layer from 55 km to 60 km.

Results

In our simulations, a planetary-scale streak structure similar to that observed by the IR2 night-side image is reproduced by strong downward flows in the vertical velocity field above the low-stability layer. Because downward flows can decrease cloud amounts and make a thin-cloud region, the reproduced streak structure is consistent with the observation. Seen from above the pole, the simulated streak structure shapes a huge spiral extending from the polar vortex to low latitudes. Such spiral may correspond to that observed by VIRTIS on board Venus Express. The streak structures on both hemispheres are synchronized, that is, the streak structures located in the same longitude. Our analyses show that the synchronization is due to equatorial Rossby-like and Kelvin-like waves with wavenumber 1, configuring vertical shear instability.

Further experiments and analyses suggest that the streaks of downward flow are caused by baroclinic instability produced around the low-stability layer with the Rossby-like waves whose phase lines are tilted by high-latitudinal strong zonal winds reinforced by the unstable waves themselves. This mechanism would be similar to that for the mid-latitude jets and baroclinic waves in the Earth atmosphere.

Acknowledgements

We thank all of the members and contributors of the Akatsuki project. This study was partly conducted under the Earth Simulator Proposed Research Project titled “Simulations of Atmospheric General Circulations of Earth-like Planets by AFES” and the simulations were performed on the Earth Simulator with the support of JAMSTEC. This study was also supported by MEXT as “Exploratory Challenge on Post-K computer” (Elucidation of the Birth of Exoplanets [Second Earth] and the Environmental Variations of Planets in the Solar System). This study was supported by JSPS KAKENHI 16H02225, 16K17809, and 17H02961.

Venus middle atmospheric simulations using AORI general circulation models

*Masaru Yamamoto (RIAM, Kyushu Univ.) and Masaaki Takahashi (NIES)

We investigate the dynamical effects of equatorial Kelvin wave on Venus' middle atmospheric circulation using a T21L72 general circulation model (GCM) with equatorial Kelvin-wave forcing and Newtonian cooling, which was developed at the Atmosphere and Ocean Research Institute (AORI) at the University of Tokyo, Japan. The dynamics are summarized by scatter plot distributions of time series of three variables (maximum zonal wind speed UMAX, meridional wind speed VMAX, and equator-pole temperature contrast dTMAX). In the scatter diagrams, the plotted points form a linear cluster for weak wave forcing, whereas they form a small cluster for strong wave forcing. In the experiment of weak 5.5-day wave forcing, an interannual (~4.5 Earth years) oscillation of the general circulation is seen and forms the linear cluster in the scatter diagram. In the region below 60 km, a pair of equatorial Kelvin and high-latitude Rossby waves with the same period produces equatorward heat and momentum fluxes. These two 5.5-day waves do not contribute to the long-period oscillation. The interannual fluctuation of the high-latitude jet core, leading to the time variations of UMAX, VMAX, and dTMAX, is associated with growth and decay of a polar mixed Rossby-gravity wave with a 14 Earth day period (Yamamoto and Takahashi 2018).

If we have room or time in this presentation, we briefly show our recent GCM results, different from the aforementioned middle atmosphere model. The dynamical effects of lower atmospheric jets on the middle atmosphere are investigated using the nudging experiments, in which the zonal mean flow is nudged to the reference flow below 40 km. The equatorial jet core appears around the cloud top in the experiment using a reference flow with the high-latitude jets below 40 km, because vertically propagating waves generated around the lower-atmospheric jets weaken the midlatitude zonal wind near the cloud top. In contrast, the midlatitude jet cores apparently form around the cloud top in the experiment using a reference flow without the high-latitude jets below 40 km. These two experiments suggest that the lower-atmospheric wind structure strongly influences the dynamics of the middle atmosphere via the vertical eddy momentum flux (Nishida 2017, Ms. thesis, Kyushu Univ.). Furthermore, we are developing the GCM with the topography and radiative transfer code based on Ikeda (2011, PhD thesis, Univ. Tokyo). The realistic simulation with the topography shows that (1) the near-surface subrotation is formed in and around high land and mountains, (2) weakly stable layer is formed at 10-20 km at low latitudes, and (3) the zonal wind is weakened at the cloud top over the Aphrodite Terra. The third result is consistent with the observed slowness of the cloud-top zonal wind around the Aphrodite Terra.

A new mesoscale model for Venus' atmosphere and its application to the bow-shaped structures discovered by Akatsuki

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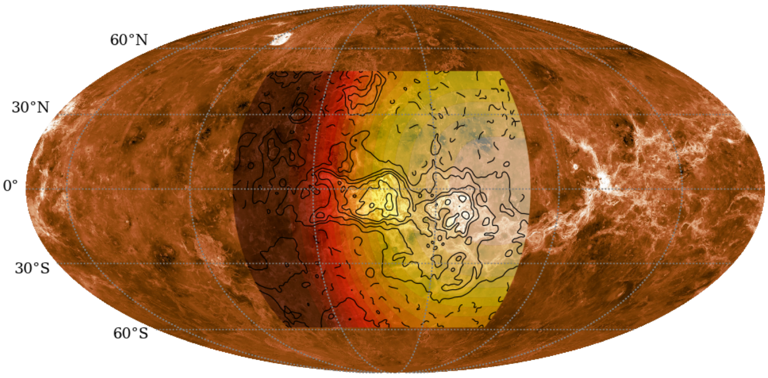

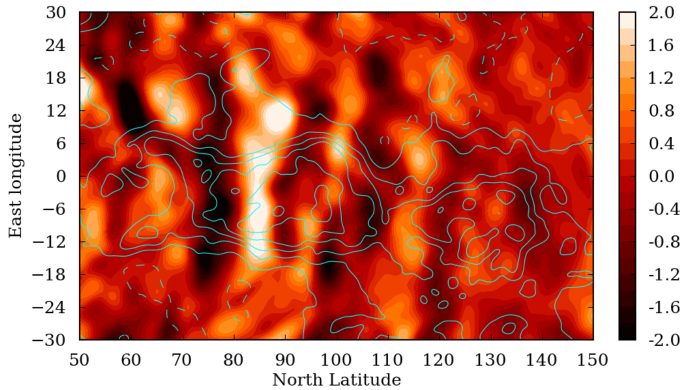

[Left figure] Incoming sunlight shown on the domain set for the Aphrodite Terra simulation with our Venusian mesoscale model, superimposed on a Magellan radar image. [Right figure] Equivalent brightness temperature at cloud top (65-72 km) as simulated by our Venusian mesoscale model at the local time shown on the left, after applying high-pass filtering as for the published Akatsuki LIR images (Fukuhara et al. 2017, Kouyama et al. 2018).

The aim of mesoscale modeling is to complement Global Climate Modeling by resolving, in a specific region of interest, the meteorological phenomena arising at spatial scales lower than a couple hundreds kilometers. Mesoscale models developed for the terrestrial atmosphere have been adapted to Mars to study the numerous small-scale perturbations evidenced by orbiting and in-situ spacecraft. To date, mesoscale modeling on Mars has been used to study slope winds, katabatic jumps, polar transients, gravity waves, dust-induced convection.

Apart from a few idealized studies, there is no mesoscale model existing for the Venus atmosphere. Results from Venus Express and the prospect of the Akatsuki mission led us three years ago to start the development of a mesoscale model for Venus. Following the same logic as the Martian mesoscale model developed in our team at Laboratoire de Météorologie Dynamique (LMD), we have now built a complete mesoscale model for Venus by coupling the dynamical core from the terrestrial Weather Research and Forecast (WRF) model with the complete physical packages developed for the Venus LMD GCM, notably the latest version of the radiative transfer. Limited-area domains can be set anywhere on Venus for our Venusian mesoscale model. High-resolution Magellan topography is used in the model. Idealized large-eddy simulations are also possible with this model and presented in a separate abstract.

Akatsuki provided the first scientific case to study with our new Venusian mesoscale model, by enabling the discovery of bow-shaped stationary structures at the cloud tops above Venus' major topographical obstacles. We will present simulations with our Venusian mesoscale model that reproduce both those signatures and their local time phasing. Our modeling study supports the interpretation of bow-shaped signatures as orographic gravity waves undergoing vertical propagation modified by the successive stability gradients they experience when propagating upwards. We will discuss the case of Atla Regio, Beta Regio and Aphrodite Terra, and detail model-observation differences and remaining challenges. Other possible modeling studies with our model (polar simulations, slope winds, ...) will be discussed and ideas of mesoscale simulations suggested by the community will be welcome.

Organization of the convection in the Venusian cloud layer.

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Abstract

1. Introduction

Venus hosts a global sulfuric acid cloud layer between 45 and 70 km which has been investigated by the Venus Express and Akatsuki mission. One of the main questions that remains unclear about the dynamics of the Venusian atmosphere is how this convective cloud layer mixes momentum, heat, and chemical species and generates gravity waves. Gravity waves emitted by the convection have been proposed to promote a significant contribution to the maintenance of the super-rotation [1]. However, these waves develop from regional to local scales and cannot be resolved by global circulation models (GCM) developed so far to study Venus' atmospheric dynamics.

2. Model

Following the idealized LES model [2] using prescribed vertical profile of heating rates extracted from GCMs runs, we coupled the Venus LMD physics to the dynamical core. The calculation of the solar and IR heating rates are done with LMD physics radiative scheme from the surface to ~100 km. The solar rate is computed with short waves radiation fluxes from Haus et al [3]. The radiative transfer is based on Eymet et al [4], using NET matrix with latitudinal varying cloud model from Haus et al [3]. As in the previous model, a third heating rate is added with an interpolated vertical profile from the LMD Venus GCM [5].

3. Results

The results shown here are for the Equator at noon with no wind shear.

The main results of this coupled LES model are the better agreement with observations of vertical extension and variability of the convective layer [6] and past modeling effort [7]. The presence of wind shear has a strong impact on the propagation of gravity waves as well as on the generation with the so-called `obstacle effect´´. Convective activity at cloud top is also present in the model while Venus Express and Akatsuki radio occultation measured stable atmosphere [8].

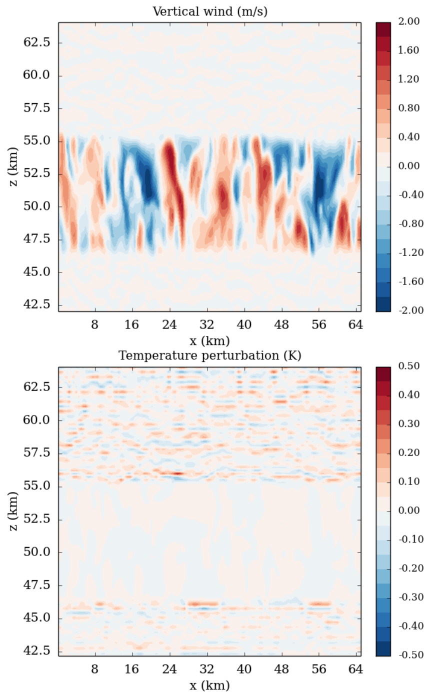

Figure 1: Top : vertical cross-section of the vertical wind (m/s). Bottom : vertical cross-section of temperature perturbation (K).

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Investigating the Influence of Wave Variations on Venus' Cloud-level Atmosphere using a Middle Atmosphere Model

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We make use of Venus middle atmosphere general circulation model simulations to determine how propagating waves influence the winds and temperature structure at cloud altitudes. We introduce wave forcing near the lower boundary of a Venus middle atmosphere model with an elevated lower boundary (details below) to simulate waves that are assumed to be propagating upwards from the lower atmosphere. In this investigation, we study the influence of propagating Kelvin and Rossby waves. We modify wave-forcing parameters and perform sensitivity tests to determine the effects of the different waves on the atmosphere at cloud altitudes. The results of simulations are validated in comparison with observations, including measurements from probes and observations from the Akatsuki and Venus Express missions. Observations at Venus' cloud levels show the presence of waves with many different periods and wavelengths, and include gravity waves, thermal tides, Rossby waves, and Kelvin waves. Using model diagnostics, we study the sources and importance of different waves, their interactions, and their changes over time.

We have developed a model of Venus' middle atmosphere, based on the Geophysical Fluid Dynamics Laboratory Flexible Modeling System spectral dynamical core. The lower boundary is raised in altitude relative to the surface to just below the cloud deck (i.e. to ~40 km altitude or ~4 x 10^5 Pa), to focus on the dynamics of the cloud-level atmosphere. The upper boundary height is around 95 km (~3 Pa). We use a Newtonian cooling radiation formulation in these simulations, based on the Held-Suarez scheme for the relaxation of temperature to a specified radiative equilibrium. We have introduced a simple linear friction "wind nudging" within the first ~2 km from the lower boundary to maintain zonal and meridional winds within observed values, since the lower atmosphere is not simulated directly in this model.

Session 09

Atmospheric Dynamics(2)

Venus atmosphere dynamics revealed by cloud tracking using images from Akatsuki

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Since its orbit insertion in December 2015, Akatsuki has been providing new discoveries on the Venusian atmosphere, which is known for thick clouds and the super-rotation with angular speeds up to several tens of times as the solid planet. This presentation will focus on dynamical aspects revealed from cloud tracking by using images at multiple wavelengths from Akatsuki. Venus is covered with clouds that extend from about 45 to 70 km altitude. Images at the near-infrared “atmospheric window” wavelengths visualize the silhouette of lower-to-middle layer clouds. From Akatsuki’s near-infrared images, it was found that a jet-like feature emerged and lasted over several months near the equator, which had never been observed previously. Also found are large-scale vortices presumably due to dynamical instability. These results suggest that winds in the lower and middle cloud layers are much more variable than have been thought. Ultraviolet imaging has long been used to observe winds at the cloud top. However, with novel two-wavelength imaging and cloud tracking with high accuracy, major advances have been provided from Akatsuki. We have succeeded in evaluating angular momentum budget regarding the super-rotation for the first time. Also found are hemispheric asymmetry that developed for a period of time and the existence of long-lasting overall vertical shear at the cloud top. Solar-longitude dependent tidal features are well elucidated, but geographically fixed features are obscure. Observational results will be compared with modelling results, and their implication on the study of the dynamics of the super-rotation will be discussed.

Part of the topics of this presentation has been published in the following papers:

Horinouchi et al. (2017) *Nature Geoscience,* 10, 646—651, doi: 10.1038/ngeo3016.

Horinouchi et al. (2018) *Earth, Planets, Space*, 70:10, doi:10.1186/s40623-017-0775-3.

The complex features and dynamics of the nightside clouds of Venus as revealed by Akatsuki and Venus Express

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The morphology of the Venus's dayside clouds and their motions have been extensively studied for about 90 years. Initial observations discovered an unknown absorber in ultraviolet images that allows to find contrasted features used to measure the superrotating winds at cloud level. The first space missions found more than 40 years ago a zoo of mesoscale cloudy features. Unfortunately, most of the observations have focused on the dayside upper clouds, and we are yet far away from a deep understanding on the role that the atmospheric dynamics play in the variety of shapes and contrasts observed on the clouds, the mechanisms behind the atmospheric superrotation or the importance of atmospheric waves and eddies. The exploration of the clouds and dynamics on the nightside of Venus delayed about half-a-century compared to the dayside, with the different Pioneer Venus and Venera probes and Vega balloons providing important data but at specific points and short instants, and not in a global hemispheric night vision of Venus clouds. Remote sensing of the night side, it presents the advantage of a wider multi-level sensing by combining observations at certain near-infrared windows (1.74, 2.32 and 3.20 μm) to observe the lower cloud's opacity and other infrared bands (3.8, 5.0, 10 μm) which permit to visualize the thermal emission of the upper clouds. The space missions Akatsuki (JAXA) and Venus Express (ESA) have revolutionized our knowledge of the nightside of Venus far beyond our expectations. Nightside clouds observed in thermal emissions show features apparently unrelated to those observed on the dayside albedo. At the upper clouds new features include: fast bright filaments which seem to alter the vertical thermal structure, shear instabilities and abundant waves which seem stationary with respect to the surface and located above elevated terrains. At the lower clouds a remarkable periodical westward-propagating cloud discontinuity –that we have missed for decades– is present at low latitudes, non-stationary waves, frequent shear instabilities and mesocale vortices. Besides, these morphologies, the superrotation at the nocturnal upper clouds is unexpectedly less homogeneous than on the dayside, while the lower clouds shows a recurrent equatorial jet, and an apparent decadal variation when observations from ground-based, Pioneer Venus, Galileo, Venus Express and Akatsuki are combined.

Long-term monitoring of planetary-scale waves in the Venus cloud top layer

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Introduction

On Venus, two types of planetary-scale waves, ~4-day Kelvin and ~5-day Rossby wave, were observed at the ~70 km cloud top with zonal wavenumber 1. They could contribute to the formation of planetary-scale features seen in the unknown absorption band at 365 nm and might be a candidate of momentum transporter to maintain the super-rotation. During previous explorations, the observed waves changed one to another in every observational period. However, since the spacecraft was operated in orbits fixed inertial space, there were significant data gaps larger than half of the Venusian year (one Venusian year is 224 days) between one and next observational period.

The purpose of this study is observing the appearance (disappearance) of the planetary-scale waves and understanding the general characteristics of them.

Observations and Analysis

We conducted ground-based continuous observations over half Venusian year by using 1.6-m Pirka telescopes in OP2015 (2015/4/21–7/17), OP2017A (2017/1/3–2/19), and OP2017B (2017/4/23–9/10). Additionally, we analyzed Venus images obtained by Ultraviolet Imager (UVI) onboard AKATSUKI. UVI observation covered partially the same periods of the ground-based as OP2017A (2016/11/6–2017/3/2) and OP2017B (2017/6/15–9/31). Over 300 days continuous data from December 2016 to September 2017 was investigated in this study, with only 50 days data missing interval in March and April 2017. We measured latitudinal relative brightness from the equatorial to mid-latitudinal regions and deduced the rotation period of waves. To capture the continuous variability in periodicity through the observational periods, we made sub-dataset with ±14 days shifting window and stepped it with the 1-day interval, and Lomb-Scargle periodogram analysis was conducted for each sub-dataset.

Results & Discussion

Two prominent modes were confirmed in our results, and 3.5–4.0-day modes were observed mainly and tended to survive for a longer time (Fig 1).

In contrast, 5-day mode sporadically appeared and sometimes last about 30 days. Zonal wind velocity at the cloud top was estimated by the cloud-tracking method (Horinouchi et al. [2017]). The measured zonal mean-wind velocity was ~100 m/s (4.4-day period rotation at the equator) and observed modes could be classified as faster (westward) propagating wave against mean-winds or slower (eastward) propagating wave. Following previous studies (e.g., Del Genio and Rossow [1990]; Kouyama et al. [2015]), the faster mode should be equatorial Kelvin wave, and the slower mode was suggested as Rossby wave in mid-latitudes.

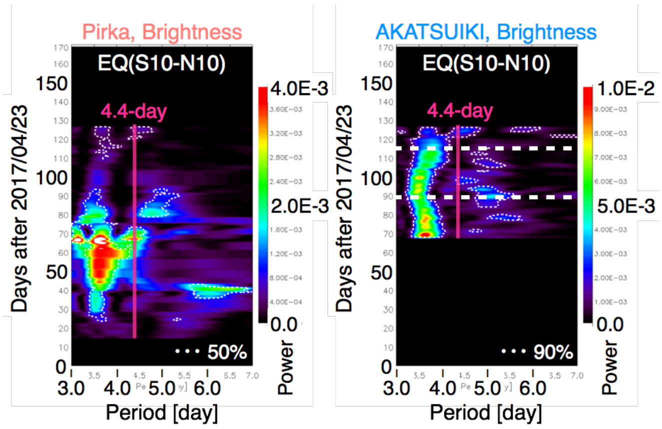

Fig 1: Temporal changes in periodicities of measured brightness variation in OP2017B observed with ground-based telescopes (left) and AKATSUKI (right).

The wave transient occurred within a sub-Venusian year, and the transient behavior could be classified into two types. One is a sporadic mode transient from 4-day to 5-day with a time scale of ~20 days. The other one is a gradual periodicity change from 4-day to 5-day.

The periodicities in the fluctuations of equatorial zonal winds were distinctly different from that in the brightness variation. One of the interpretation is that 5-day wave in mid-latitudes has the more significant amplitude of fluctuating winds than 4-day wave at the equator. In parallel, another possible explanation is acceptable that the 4-day wave observed with planetary-scale features reflects at a lower altitude than the that of the 5-day wave measured by mesoscale cloud tracking.

Meridional and Zonal winds at Venus' atmosphere from Cloud-tracking, Doppler techniques and comparison with modelling

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We present final results of the meridional wind in both Venus' hemispheres and spatial and temporal variability of the zonal wind, based on coordinated observations at Venus cloud-tops based with two complementary techniques: Ground-based Doppler velocimetry and cloud-tracked winds using ESA Venus Express/VIRTIS-M imaging at 0.38 μm. Cloud-tracked winds trace the true atmospheric motion also responsible for the Doppler-Fizeau shift of the solar radiation on the dayside by super-rotating moving cloud-tops with respect to both the Sun and the observer (Machado et al., 2014). Based on this complementarity, we performed a new coordinated campaign in April 2014 (Machado et al., 2017) combining both Venus Express observations and ground-based Doppler wind measurements on the dayside of Venus' cloud tops at Canada-France-Hawaii telescope at a phase angle $\Phi = (76\pm0.3)^o$. Venus Express cloud top wind measurements based on tracking using images taken with the VIRTIS instrument indicate nearly constant zonal winds in the Southern hemisphere between 0 and 55° S. The analysis and results show (1) additional confirmation of coherence, and complementarity, in the results provided by these techniques, on both spatial and temporal time scales of the two methods; (2) first-time estimation of the meridional component of the wind in other planet using the Doppler velocimetry technique, with evidence of a symmetrical, poleward meridional Hadley flow in both hemispheres; (3) spatial and temporal variability of the zonal flow with latitude and local time, with a significant increase of wind amplitude near morning terminator.

We also present final results based on observations of Venus' bottom of the cloud deck, carried out with the Near Infrared Camera and Spectrograph (NICS) of the Telescopio Nazionale Galileo (TNG), in La Palma, on July 2012. We observed for periods of 2.5 hours starting just before dawn, for three consecutive nights. We acquired a set of images of the night side of Venus with the continuum K filter at 2.28 microns, which allows to monitor motions at the lower cloud level of the atmosphere of Venus, close to ~ 48 km altitude. Our objective is to measure the horizontal wind field in order to characterise the latitudinal zonal wind profile, to study variability, to help constrain the effect of large scale planetary waves in the maintenance of superrotation, and to map the cloud distribution.

We will present results of cloud tracked winds from ground-based TNG observations and winds retrieved from coordinated space-based VEx/VIRTIS observations. The observational results will be compared with the ground-to-thermosphere 3D model developed at the Laboratoire de Meteorologie Dynamique in Paris (Gilli et al. 2017), whose zonal wind predictions above 60 km seem to be consistent with available measurements (Peralta et al.2018).

Detection of large stationary gravity waves over six Venusian solar days seen in LIR images

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Abstract:

The existence of large stationary gravity waves was discovered during Akatsuki's first observation sequence in December 2015 (Fukuhara et al., 2017). Since the discovery, large stationary gravity waves have been detected periodically in mid-infrared images by LIR onboard Akatsuki (Kouyama et al., 2017). The waves showed clear topographical and local time dependence in which the waves periodically appeared mostly above four specific highland regions in the low latitudes (Aphrodite Terra, Thetis Regio, Atla Regio, and Beta Regio) and they became significant in the local afternoon (Kouyama et al., 2017).

In this study, we will show the further detection of stationary gravity waves seen in LIR images over six Venusian solar days. As described in Kouyama et al. (2017), the waves appeared again and again above the four highlands mainly when they were in local afternoon. Figure 1 shows examples of Aphrodite Terra case. In addition to the large-scale features, rather small stationary waves have been identified above other locations where are nearby local peaks. There has been no detection of a stationary wave signature above Ishtar Terra, which has the highest mountain in Venus, Maxwell Mons, but locates in higher latitudes (> 60°). The clear dependence of stationary waves on location and local time indicates that the excitation and propagation of stationary waves may be controlled by the solar heating during the daytime and the consequential change in the atmospheric structure. Thanks to the clear dependence, we may predict future appearance of stationary waves which will help to plan future observations by both Akatsuki and ground-based.

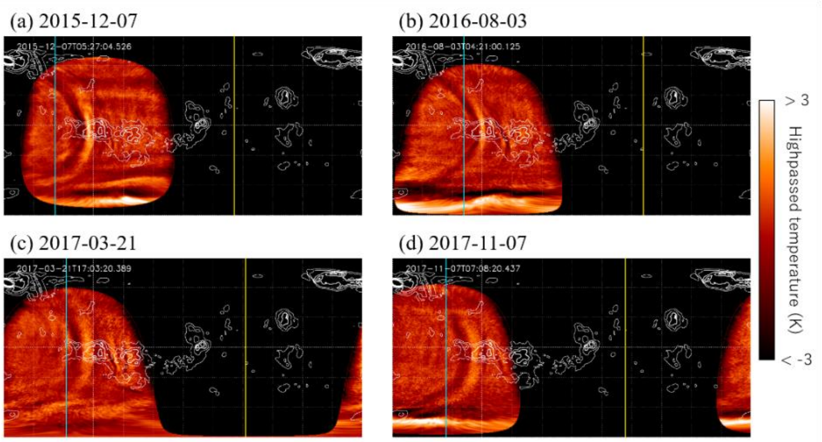

Figure 1. Stationary gravity waves above Aphrodite Terra in LIR images from 2015 to 2017. Orange and blue lines indicate morning and evening terminator, respectively.

We have observed the nightside of Venus from NASA's Infrared Telescope Facility (IRTF) near the dates of inferior conjunctions from May 2002 through May 2017. Over 65 separate evening or morning apparitions have been observed in total. Using the IRTF's SpeX instrument, we obtained simultaneous images (with the SpeX guide camera) and spectra (in one of the 60" long-slit spectral modes). The images are taken with a narrow (1%) 2.26 μm filter that corresponds to a CO_2 transmission window or an adjacent filter at 2.16 μm where CO_2 is opaque. In the 2.26 μm filter, nightside clouds in Venus' lower and middle cloud decks are visible as silhouettes against the thermal emission from Venus' surface and lower scale heights (Fig. 1). The 2.16 μm images are useful to model and subtract scattered light from Venus' dayside crescent.

The IRTF is capable of imaging Venus during daylight. Some observing sessions can last up to four hours, although cloud motions are clearly discernible after an hour. We often scan the slit of the spectrometer across Venus' disk while we are taking images: in this way we obtained spectral image cubes at the same time that we obtained cloud-tracking image sequences. The image cubes cover 0.8 to 2.5 μm at coarse spectral resolution (R = 200 to 500); they can be used to determine cloud particle sizes and concentrations of CO.

The Akatsuki spacecraft's IR2 camera was designed to track clouds and CO concentrations over Venus' nightside as well, in filters at 1.74, 2.26 and 2.32 μm. Under good conditions, the IRTF image quality is 0.5" (full-width at half-maximum of the point spread function at 2.26 μm), equivalent to about 120 - 150 km on Venus' surface. While this spatial resolution is several times poorer than the IR2 images obtained from most points in Akatsuki's orbit, it is nonetheless sufficient to estimate wind speeds (from cross correlations of cloud fields) at the 5 m/s level given image sequences that span 3 hours, or 3 m/s wind resolution under the best of conditions. This level of velocity resolution lets us

- Determine latitudinal wind profiles on a day-to-day basis,
- Observe variability in wind speeds at certain latitudes, and
- Look for secular changes in winds over a 15-yr period.

One data set consists of 13 morning observations spread out over 17 days in April and May 2017 (Fig. 1). We have applied for time to observe Venus in 2018, from Sept. 12 to October 14 and Nov. 10 to Dec. 10, surrounding the time of the upcoming inferior conjunction on 27-OCT-2018. The motivation for these observations are not only to confirm the Akatsuki -based results showing variable equatorial jets (Horinouchi et al. 2017), but also extend the cloud-top observations of stationary waves on Venus' nightside (Peralta et al. 2017) to the middle and lower cloud decks, where they have so far been undetected.

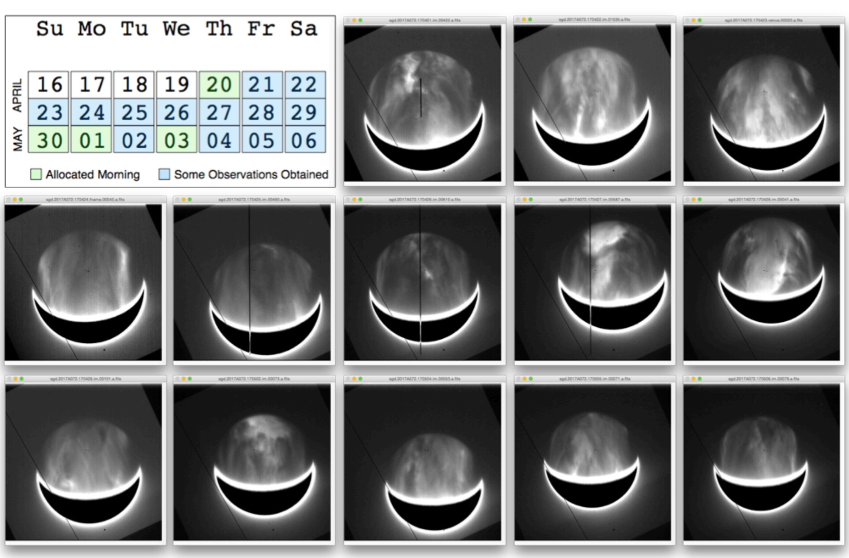

Fig. 1
Images of Venus obtained from 21-APR-2017 to 6-MAY-2017 from the IRTF/SpeX instrument. Blue calendar dates represent the 13 successful mornings of observations, green dates were spoiled by bad weather. North is to the left in these frames. In some frames the spectral slit is visible. Most images were part of a sequence that lasted 1 to 4 hours, into daylight.

Cloud morphology and wind measurements by the Akatsuki 1-μm camera

Iwagami N* (none) and J. Peralta (Japan Aerospace Exploration Agency)

Venus is often called as a sister of the Earth because of its similar size and distance from the Sun. However, their resemblances end here, since the Venus atmosphere is mostly composed of CO_2 and a surface pressure and temperature as high as 90 atm and 740 K, respectively. Its atmosphere is dominated by a phenomenon called “super rotation”, which has been investigated by meteorologists for more than half a century manifesting as fast wind speeds that at the cloud top achieve velocities of ~100 m/s, 60 times faster than that of the solid globe. However, the accelerating mechanism is still unknown. Remote wind measurements on Venus have been conducted mainly in the UV region, where the presence of an unknown absorber allows the tracking of clouds. On the contrary, cloud tracking with images in infrared wavelengths (which allow to sense a deeper level than UV images) is difficult due to the faint contrast of just a few percent.

Here we present the analysis of 900-nm images of Venus’s dayside clouds, taken by the IR1 camera onboard JAXA’s Akatsuki mission. We have inspected 984 images covering from 07 December 2015 to 09 December 2016, attending to suitable values of spatial resolution and phase angles. We investigate both global and local properties of the clouds to see their temporal and spatial variations in 900-nm images. A comparison with UV images is also undertaken to gather information about acceleration processes at different contrast-forming heights. Considerable hemispherical asymmetries and sharp changes are sometimes observed in the images. The zonal and meridional wind profiles found are similar to those of previous IR measurements but displaying a profile closer to a solid-body rotation, transiting from the expected profile of a constant wind speeds to frequent episodes of unexpected strong equatorial jets. This may indicate that contrasts at 900-nm may be at least partly formed by the unexpected unknown absorber which may act as a heating source in the middle and lower cloud region.

Session 10

Atmospheric Dynamics(3)

Morphology of thermal structures at the Venusian cloud-tops

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Longwave Infrared Camera (LIR) onboard Akatsuki has been functioning quite normally, and more than 18,000 images have been acquired since the Venus orbit insertion in December, 2015. LIR usually takes an image every one or two hours with accumulation of 32 raw images acquired during two minutes when the spacecraft is approximately 80,000 km or further apart from Venus, and every two seconds, two or five minutes without accumulation when the spacecraft is closer to Venus than this distance. Image data downlinked to the ground go into the data processing pipeline, and a dataset of brightness temperature distributions is created. Since the altitude from which the most of thermal emissions contribute to the detected signal becomes higher as their zenith angle becomes larger, LIR detects thermal emissions from the cloud-tops at an altitude of ~65 km in the low latitudes around the center of the Venus disk and from an altitude of ~70 km where is 7 to 8 km higher than the nominal cloud-tops at the polar region. It is the first time ever such a large number of brightness temperature distributions at the cloud-tops are obtained. They make it possible to systematically and statistically categorize characteristic thermal structures at the cloud-tops. Large-scale bow-shaped thermal structures have been found to be temperature modulations by stationary gravity waves generated in the lower atmosphere. Bow-shaped structures with smaller scales have also been detected. They show similar shapes and stationarity as the large-scale bows, but what the difference in the horizontal scale means is unknown. These stationary features could be a probe to diagnose the condition deep beneath the thick cloud layer. The polar dipole is the brightest feature when it is seen in the Venus disk, as the brightening effect due to observation geometry enhances its high temperature. The rotation periods of the polar dipoles observed in 2016 and 2017 are estimated to be significantly longer than the values obtained from the past observations. However, a more careful analysis would be required to conclude it, because the polar dipoles show complicated motion. LIR detects a variation in brightness temperature due to a thermal tide, which will be presented by Kouyama et al. in detail. Wavy structures with a horizontal wavelength of an order of ~100 km are identified in the low and middle latitudes. Cell-like or irregular structures with a small temperature variation close to the detection limit of LIR are also identified. Thin zonal structures sometimes appear in the high latitudes. Generation mechanisms of most of these characteristic features summarized here are being investigated.

Interactions between the topography and the atmosphere on Venus

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A major discovery of the Akatsuki spacecraft is the presence of a massive 10,000 km long bow-shaped wave at the cloud top, stationary with the surface [1]. This wave is a mountain wave, occurring at multiple locations over equatorial highlands in the afternoon [2]. This is indicative of a direct influence of the surface on the atmosphere at altitudes as high as the cloud top (70 km).

In order to investigate this wave, a Global Circulation Model (GCM) is a tool of choice, especially since measurements of the deep atmosphere of Venus are very limited. In this study, we used the Institut Pierre-Simon Laplace (IPSL) Venus GCM. It includes a realistic topography from the Magellan mission and its effects well below the horizontal resolution (typically 300 km at equator) via a gravity wave drag parameterization [3,4]. This capability allows us to explore the conditions for the creation of the bow-shaped wave, and its dependence on local times. A very good match between the model and the observations from 4 solar days of observations by Akatsuki [2] is obtained, both temporally and spatially.

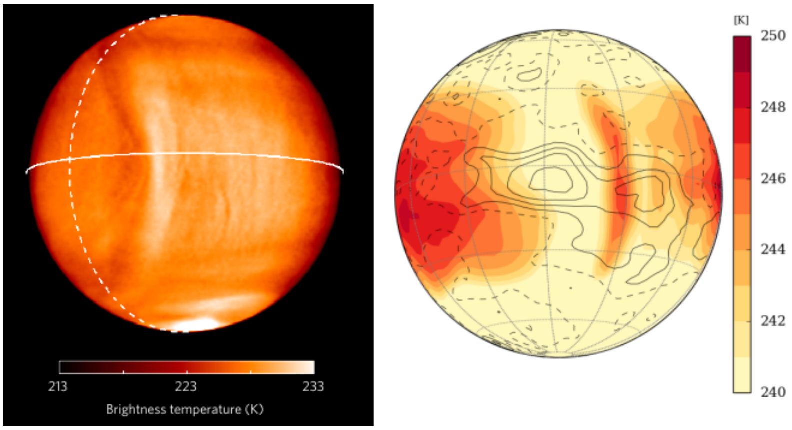

Figure : Mountain wave at the cloud top seen as a disturbance in the brightness of the cloud top [1] (left), and in the simulated temperature field of the IPSL VGCM [2] (right).

These mountain waves contribute to a substantial part of the exchange of angular momentum between the surface and the atmosphere. The other contributions come from the diurnal thermal tide and surface baroclinic waves with the same period as the super-rotation. The angular momentum and its exchange between different physical systems (atmosphere, solid body, Sun) is crucial to understand Venus and some of its unique features, such as the super-rotation of the atmosphere and the retrograde spin of the solid body.

In the light of this recent discovery and modeling of Venusian mountain waves, it appears that atmospheric measurements within and above the cloud deck can now directly inform us on the circulation at the surface. Moreover, the instantaneous rotation of the solid body and its fluctuations are also very desirable measurements that could inform us on the rate of momentum exchange with the atmosphere.

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Acknowledgments

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The Long-wave infrared camera (LIR) on board Akatsuki detects thermal infrared radiation at wavelengths of 8–12 μm from cloud-top level (65 km) of Venus in order to provide brightness temperature map. LIR mainly has obtained Venus disk images with more than 50,000 km distance along Akatsuki's elliptical orbit. Meanwhile, LIR obtained more than 500 of close-up images at equatorial region with fine spatial resolution. In this study, temperature deviations were derived from the close-up images in latitude from 30 to -30 degree. After that, zonal wave-number spectra of the temperature deviation at mesoscales (wavelengths of 20–1000 km) were obtained in 5 degrees step of latitude as a function of local time (LT). The result shows that the temperature deviation is obviously high in LT 14:00–18:00, and the spectral peak corresponds to the wavelengths of 500 km. The temperature deviation would be caused by the stationary gravity wave discovered by LIR initial observation (Fukuhara et al., 2014, Nature Geo). We could detect the stationary gravity wave in the LIR image not only in the Venus disk image but also in the close-up image. Another high temperature deviation is seen in LT ~23:00, and the spectral peak corresponds to the wavelengths of ~150 km. A previous numerical simulation (Imamura et al., 2014, Icarus) has predicted that temperature deviation at the cloud-top level can be caused by upward propagation of the gravity wave, which is generated by the convection in the cloud layer of the night-side of the equatorial region. Our result can support existence of such upward propagation of the gravity wave in the cloud level of Venus.

Planetary ageostrophic instability leads to superrotation

The mechanism giving rise to spontaneous superrotation in global circulation model (GCM) simulations involves a global instability that couples an equatorial Kelvin wave to mid- or high-latitude Rossby waves in the presence of a substantial meridional shear; we refer to this as 'planetary ageostrophic instability'. We demonstrate planetary ageostrophic instability using a global primitive equation eigenvalue solver, and further show that intermediate values of a 'bulk Froude number', Fr, a measure of the meridional Doppler shift relative to equatorial gravity wave phase speeds, are required for the instability. The linear model shows that values of the Rossby number (Ro) and Fr in the atmospheres of Earth, Mars and Titan are consistent with the existence of superrotation only on Titan. Although Venus' parameters are beyond the range studied, the presence of Kelvin- and Rossby-like waves in the cloud layers suggest a similar mechanism may be responsible for superrotation in Venus' cloud-level atmosphere. More generally, dry GCM simulations with hemispherically and zonally symmetric forcing spontaneously transition to superrotation provided (a) the Hadley cell is not too strong and (b) baroclinic instability is suppressed. The former condition is met with sufficiently weak thermal forcing and the latter condition is met in high-Rossby-number (Ro) regimes.

Gas dynamics simulation of the general circulation of Venus atmosphere

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The first non-hydrostatic general circulation model of the Venus atmosphere based on the full set of gas dynamics equations is adapted to the high resolution grid, involving 480 nodes in the vertical, 768 in latitude and 384 in longitude. Such a non-uniform horizontal resolution is selected with the purpose to reproduce the dynamics of the polar vortices in more details than it has been achieved in previous studies. Navier-Stockes equations, along with energy balance, continuity, and equation of state, are being solved by an original second-order scheme implementing a semi-Lagrangian finite volume method, characterized by monotoneous behavior, high degree of mass conservation, and zero linear viscosity. The CFD solver is implemented in on CUDA platform and ported to the commercial GPU hardware, resulting is more than 100-fold acceleration compared to single-thread calculations.

The model takes into account Venus relief, solar heating and radiative cooling, and convective processes in the atmosphere, which in particular results in the enhanced heating of the polar atmosphere above the cloud layer. Simulations suggest that such heating facilitates the effective damping of superrotation at the altitudes of 80-90 km and transition to the subsolar-antisolar circulation at higher altitudes. The dynamics of the transition region is determined by a sharp decrease of mean zonal flow caused by fading superrotation, with complex flow pattern, developing large-scale turbulence and dissipation of substational amounts of heat, which in turn results in the appearance of a narrow warm layer in this altitude range. In the polar regions the model predicts irregular rotating structures resembling terrestrial hurricanes. Simulations suggest that the dynamics of polar vortices in the Venus atmosphere affects global circulation pattern, in particular, the transition from superrotation to the subsolar-antisolar circulation.

Maintenances of Venusian Sulfuric Acid Clouds and SO_2 Abundances due to Chemistry and Dynamics Simulated by a General Circulation Model

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Abstract

Sulfuric acid clouds are important in the determination of Venusian climate through their radiative processes, and the main observational object of the Japanese Venus Climate Orbiter “Akatsuki” for the investigations of atmospheric dynamics. We have implemented the sulfuric acid cloud formations and related chemical processes into a Venusian General Circulation Model (VGCM) developed by Ikeda (2011), and investigated their distribution and the formation systems. The implemented chemical processes include the reactions to determine the abundances of H_2SO_4 vapor, SO_3, SO_2 and H_2O, and are critical in the reproduction of the realistic cloud maintenance processes. With the chemical processes, the simulated latitudinal distributions of the optical thickness of clouds qualitatively agree with the observational results by the Visible and InfraRed Thermal Imaging Spectrometer (VIRTIS) onboard Venus Express (VEX), and also the simulated vertical profiles of H_2SO_4 vapor agree with the Magellan radio occultation data, in low- and mid- latitudes (0-60 degrees). With this model, we investigated the maintenance and circulation processes of the sulfuric acid clouds and vapor in the latitude regions. Our model indicated that, in the upper cloud region (60-80km), the production of clouds by the condensation of H_2SO_4 resulting from chemical processes is the largest at ~65 km altitude, and the clouds are advected upward and poleward by the meridional circulation and vertical diffusion. Meanwhile, in the lower cloud region (50-60km), H_2SO_4 vapor transported by the advection and vertical diffusion condenses into the cloud in the equatorial region of 50-54 km altitude, and the formed clouds are transported poleward along the meridional circulation. These cycles are consistent with those simulated in a 2-D latitude-altitude model by Imamura and Hashimoto (1998), and we first reproduced the cycle with a 3-D model. In the presentation, comparisons of the simulated results of SO_2 distributions with the observations by the Spectroscopy for Investigation of Characteristics of the Atmosphere of Venus (SPICAV) onboard VEX and ground-based telescopes will also be shown.

Session 11

Atmospheric Structure

Climate control on Venus: Connections among clouds, UV absorber, surface chemical reaction, and atmospheric circulation

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It has been suggested that the climate of Venus is controlled by atmospheric SO_2 concentration (e.g., Hashimoto and Abe, 2005). Although SO_2 is a minor constituent of Venus' atmosphere, there are several ways to affect the energy balance of Venus. The atmospheric SO_2 concentration is likely related to the planetary albedo, since SO_2 is a precursor material of Venus' sulfuric acid clouds which cover the entire planet. Also the absorption of solar radiation is controlled by the distribution of unknown UV absorber, and some of sulfur bearing species have been suggested as candidates for the unknown UV absorber.

On the other hand, it has been argued that the abundance of atmospheric SO_2 concentration is controlled by chemical reactions between the atmosphere and planetary surface. Since chemical reaction depends on the temperature, surface chemical reactions would create climate feedback loops. It has been discussed that types of feedback loops depend on the assumption of materials on the Venus' surface (e.g., Hashimoto and Abe, 2005). To understand the stability of Venus' climate, it is necessary to elucidate the materials on the surface of Venus.

I suggest that the meridional circulation is also connected to climate feedback loops. Some of the surface chemical reactions are controlled by the oxygen fugacity at the surface of Venus which is likely affected by transport of CO produced by photochemical reactions in the upper atmosphere. Since the strength of the meridional circulation is influenced by the distribution of the absorption of solar radiation, it is reasonable to suppose that it creates climate feedback loops. It would be worth to examine the role of atmospheric circulation on the CO transport and the climate feedback loops.

Understanding the Millimeter Wavelength Continuum Emission from Venus

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Microwave observations of Venus from Earth-based radio telescopes have provided valuable information about the lower atmosphere and surface conditions of the planet. The increased resolving power of modern interferometric telescope arrays permits spatial mapping of Venus from microwave to millimeter wavelengths using both broadband and narrowband channels. Narrowband millimeter and submillimeter observations of Venus have been used to determine distributions of several trace species and to map wind patterns in the mesosphere [1, 2]. Broadband observations of continuum emission, however, are more difficult to interpret in a meaningful way

Images of Venus from the Hat Creek Interferometer and the Nobeyama Millimeter Array suggest substantial localized variations in the 2-4 millimeter continuum emission across the disk of the planet [3, 4]. Since emission at these wavelengths reflects atmospheric processes just below the cloud deck of Venus, these variations in measured brightness temperature (> 30K) were thought to be linked to variations in the abundance of H_2SO_4 vapor between 38 and 50 kilometers above the mean surface. However, recent laboratory measurements of H_2SO_4 vapor opacity at millimeter wavelengths suggest that variations in H_2SO_4 vapor abundance are not likely the cause of the emission abnormalities. This result implies that the observed fluctuations in brightness temperature at Venus are the result of a different process. We consider several of these processes to determine their likelihood.

The dominant vapor-phase microwave absorbers in the troposphere of Venus are CO_2, N_2, H_2SO_4, and SO_2. This list excludes H_2O, OCS, CO, and HCl, as these constituents have been determined to have a negligible contribution to the observed continuum emission at longer millimeter wavelengths [5,6]. Additionally, laboratory measurements of the dielectric properties of liquid sulfuric acid suggest that the cloud aerosol variations are not the source of substantial emission As fluctuations, even considering charged aerosol conditions [7]. Furthermore, *in situ* data from landers and balloon platforms suggest that the temperature variations with longitude are at most 10 K between the 38 and 50 kilometer altitude range with little diurnal variation [8]. This leaves two possibilities for the source of millimeter wavelength continuum emission variations: substantial fluctuations in cloud-base SO_2 abundance or the presence of virga.

The likelihood of each scenario is explored using a radiative transfer model incorporating laboratory measurements of microwave absorption for tropospheric constituents, temperature-pressure profiles from the Venus International Reference Atmosphere, and constituent abundance profiles from chemical models, radio occultations, and *in situ* cloud data from the Pioneer Venus Mission. In addition, the atmospheric processes contributing to each of these scenarios is considered. Although the millimeter wavelength emission variations do not immediately appear to be linked to topographical features, perturbations of global circulation due to large gravity waves may be responsible for temporarily altering the abundances of opaque gases or aerosols. Coordinated observation of Venus using both microwave and millimeter wavelength sensing platforms are needed to provide insight into the processes behind this curious phenomenon.

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Local time-dependent structures in and below Venusian clouds revealed by Akatsuki radio occultation experiments

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Though the temperature of the lower atmosphere of Venus does not change much during one Venus solar day, local solar time-dependent phenomena are still considered important as driving forces of the atmospheric circulation. For example, thermal tides generated by the periodical solar heating of the cloud layer can transport angular momentum to affect the zonal circulation. Especially the tides propagating downward below the cloud can play a crucial role in the maintenance of the super-rotation of the atmosphere because they can induce exchange of angular momentum between the atmosphere and the solid planet (Takagi and Matsuda 2007). At mesoscales, because solar heating of the upper part of the cloud tends to stabilize the vertical stratification, convection in the cloud is expected to become stronger on the nightside than on the dayside (Imamura et al. 2014). Such a diurnal variation of vertical mixing should influence the global cloud structure. These theoretical predictions, however, have not been fully examined based on observations.

The radio occultation measurement of the Akatsuki mission, termed RS, aims at the exploration of the vertical structure of the atmosphere (Imamura et al. 2017), being complementary to the imaging observations by the onboard cameras. Akatsuki RS mainly probes the low and middle latitude regions because of the near-equatorial orbit in contrast to the previous radio occultation experiments using polar orbiters. The change of the atmospheric structure along the local solar time in the low latitude is one of the main topics of RS.

The observations conducted in 2016-2017 cover broad local time regions in the low latitude, enabling characterization of local time-dependent structures. The vertical extent of the cloud-level neutral layer, which is thought to represent convective mixing, is found to change with local time. Signatures of upwardly-propagating tides above the cloud are clearly seen. Notable variations are seen also in the sub-cloud region down to ~40 km in temperature/pressure profiles. Results of the analysis including data taken in the first half of 2018 will be presented and their implications for the atmospheric circulation will be discussed.

Mean thermal structure in the Venusian lower atmosphere investigated by Venus Express and Akatsuki radio occultation measurements

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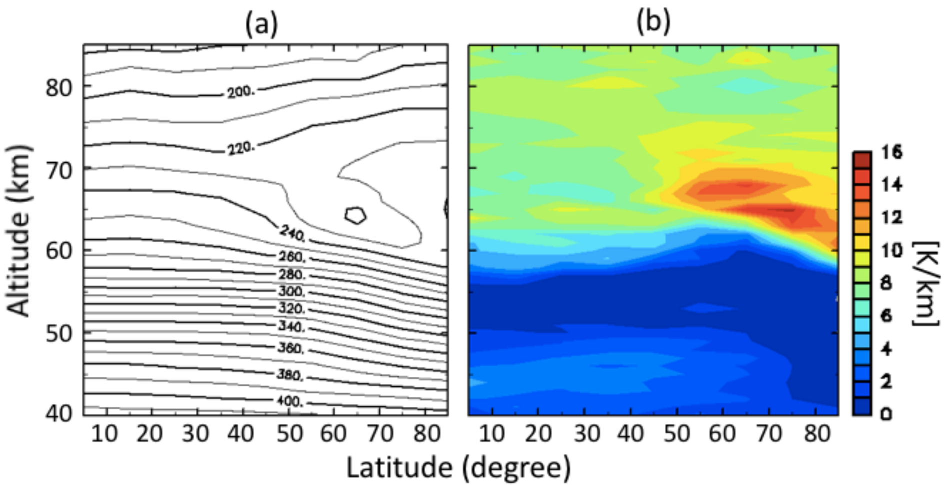
Unlike Earth and Mars, it is difficult to investigate the thermal structure in the lower atmosphere of the Venus because the thick cloud layer surrounds the planet globally. Radio occultation technique enables us to retrieve a vertical temperature profile with high accuracy and high vertical resolution, which is helpful for us to know a planetary thermal environment. In this study the mean Venusian thermal structure was investigated down to 40 km altitude, which is lower than the Venus cloud bottom level (~50 km altitude), by Venus Express and Akatsuki radio occultation measurements. At the latitudes equatorward of 75°, the mean static stability distribution is qualitatively consistent with previous in-situ measurements; there is a low stable layer at 50–58 km altitudes, and high and weak stable layers exist above and below it. At the latitudes poleward of 75°, the low stable layer extends at the altitudes of 42–58 km continuously, which has not been shown by any observational studies. This unique static stability distribution in the Venus polar region might be attributed to the latitudinal difference of solar heating in the upper cloud, the structure of the mean meridional circulation in and below the cloud layer, and the existence of submicron sulfuric acid haze above the cloud layer.



Latitude-height distributions of the zonally and temporally averaged (a) temperature and (b) static stability obtained by Venus Express and Akatsuki radio occultation measurements.

The puzzling transition region of Venus atmosphere studied by a ground-to-thermosphere 3D model

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Introduction: The middle/upper atmosphere of Venus, notably between 70 and 120 km, is the so-called "transition region" between the retrograde superrotating zonal flow dominating below 65 km, and the day-to-night circulation above 120 km. Venus Express observations (2006-2014) showed that this region is more variable than expected, with latitudinal and day-to-day variations of temperature up to 80 K above 100 km at the terminator [1], and apparent zonal wind velocities measured around 96 km on the Venus nightime, highly changing in space and time [2]. Those variations are not fully explained by current 3D models and specific processes (e.g. GW propagation, thermal tides, large scale planetary waves) responsible for driving them are still under investigation.

This work: We propose to use the current improved version of the *LMD* Venus General Circulation Models (VGCM) [3,4] to yield insight into the global circulation of this region by fostering data-model synergies. Zonal wind predictions above 60 km by our VGCM showed to be consistent with available measurements [5]. On-going ground-based Venus observation on the cloud tops (~70 km) and below [6] will add complementary information to understand the coupling between the lower and upper atmosphere of Venus.

In addition, observed $O_2(^1\Delta)$ nightglow, CO and O density [7,8,9], usually considered as sensitive transport tracers in the upper atmosphere of Venus, where no direct wind measurements are available, will be interpret with the help of 3D model results.

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A fully coupled photochemical-condensation model of the Venus atmosphere from ground to 110 km

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Ground based, Venus Express, and Akatsuki observations have provided a wealth of information on the vertical and temporal distribution of clouds and many chemical species in the Venusian atmosphere [1, 2,3]. Previous modeling efforts have focused on either the gas chemistry [4-6] or the sulfuric acid aerosols [7,8], and also typically modeled the lower (0-50 km) and middle (40-100 km) atmospheres separately. In the middle atmosphere of Venus, the chemical reaction $H_2O + SO_3 \rightarrow H_2SO_4$ is highly energetically favored. As such, chemical models generally struggle to self-consistently calculate SO_X and H_2O abundances. To avoid this, many models hold the concentrations of the condensible species, H_2O and H_2SO_4, fixed [4,5]. In models where these species are calculated self-consistently the model results are highly sensitive to the boundary conditions in the cloud level [8].

In this work we introduce a new photochemical-condensation framework to understand the interaction among gas, haze, and cloud in Venus' atmosphere. First, we extend the domain of the 1D photochemistry model of Zhang et al. (2012) [5] to encompass the region between the ground and 110 km and implement a simple condensation scheme of sulfuric acid clouds with gravitational settling. We simultaneously solve for the chemistry and condensation allowing for self-consistent cloud formation. With this model we aim to reproduce the following observations of which a satisfactory explanation has been lacking so far:

- Near constant water vapor mixing ratio in the middle atmosphere [10]
- SO_2 vertical profile including an inversion at high altitudes (>70 km) [2]
- H_2SO_4 gas mixing ratio and cloud acidity measurements [1,11,12]

We find that the vertical abundance of water vapor can be explained by assuming its abundance is buffered by condensation and evaporation. The main free parameter in this modeling is the cloud acidity. Using a single cloud acidity profile we can also match observations for the H_2SO_4 vapor.

We further investigate the interaction between the vapor and particles in the microphysical model CARMA [7]. We input the sulfuric acid vapor production rate and water vapor loss rate from our photochemical model into CARMA to create a self-consistent H_2O-H_2SO_4 gas-cloud microphysics model of Venus. We find that condensation-chemistry interactions could stabilize the H_2O-H_2SO_4 system. We will also discuss the implications this has for the sulfur mass budget and dynamics of the middle atmosphere.

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Title: On Venus' Cloud Top Chemistry, Convective Activity and Topography: A Perspective from HST

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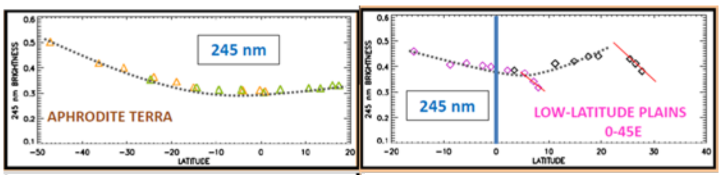
Venus' 245 and 365 nm cloud top albedo is derived from 2010/2011 HST/STIS spectra [1-2] that were obtained at Venus local solar times (LST) of 7 to 11:30 a.m. above two regions of distinct topographical elevation. In each case the cloud top albedo was observed to increase smoothly with increasing latitude as is expected if the distribution of the cloud top absorbing species is dominantly controlled by Hadley cell circulation. However, above low-latitude (≤ 30 N) plains regions the albedo was observed to darken rapidly as the LST increased from 10 a.m. towards noon. The local time at which the darkenings manifested suggest a direct link to the previously observed and well documented subsolar convective activity that manifests at Venus' cloud tops within 2 hours of local noon [3-5]. However, the absence of the darkenings above the low-latitude regions intersecting the Aphrodite Terra mountains at similar local times suggests that the process(es) producing the near-noon darkening above the plains regions is somehow ineffective or delayed above Aphrodite.



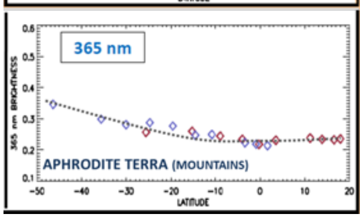


Figure 1: Venus' 245 and 365 nm cloud top albedo increases with increasing latitude as is expected if the distribution of the cloud top absorbing species is dominantly controlled by Hadley cell motion. Deviations from the smooth latitude variation curve are evident above the plains regions (indicated by red lines), at latitudes near 10 and 30 N at Venus local times between 10 a.m. and noon. No deviations are evident in the data obtained over the Aphrodite Terra mountains at any Venus LST between 7 and 11:30 a.m.

Models of the subsolar convective mixing mechanism (e.g., [6]) show that excitation of convective activity that expands from the boundary between the middle and upper clouds to the cloud tops can have significant impact on the transport of materials from the middle cloud to the cloud tops. These models also show that the vigor (vortex velocity and eddy mixing rate, κ_m) of the convective activity and the atmospheric stability gradient at the point of excitation determines the altitude range over which gases and trace species such as the unknown absorber(s) may be transported. RT modeling implies the change in SO_2 abundance inferred from the HST/STIS spectra at LTs between 10 and noon could not produce the darkening observed at 245 nm above the plains [1-2,7] thus, the simplest explanation for the darkening at 245 nm is upward mobilization of one or more of Venus' unknown absorbers [e.g., 8-11] via sub-solar convective activity. Thus, the HST observations provide additional evidence that Venus' unknown absorber may have multiple sources and/or that at least one species has a continuum extending shortward of 300 nm [12-13]. However, the terrain dependence must also be explained.

Recent Akatsuki 10±2 μm images reveal planetary-scale gravity waves (GWs) at the cloud top level above Aphrodite Terra whose surface excitation and cloud top manifestation onsets between 10 and 11 a.m. Venus LST [14]. Comparison of these results with the HST results and the subsolar convective cell models suggests the passage of the GW may interfere with the small scale mixing rate, slowing the transport of traces species from the middle to the upper clouds and delaying/preventing any LST darkening that may occur at the cloud top level. Combining the HST results with work by [15] implies that topography impacts the vertical distribution of Venus' unknown absorber(s) through both large and small scale mixing mechanisms. This implies that monitoring Venus' cloud top signature relative to LST and topography is important for tracing and diagnosing the drivers that influence the vertical and horizontal distributions of the unknown absorber(s). Thus, we strongly advocate for future observations that can uniquely characterize Venus' LST cloud top properties relative to Venus' underlying surface topography.

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The Dust Cycle on Venus

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Before the greenhouse effect due to carbon dioxide on Venus was fully recognized, the idea that wind friction and dust in the lower atmosphere (the 'aeolosphere') might warm the surface was advance by Öpik (1861), and a dust insulation model was explored by Hansen and Matsushima (1967). Like many "wrong" ideas in science, these hypotheses may yet contain an element of truth.

Measurements by the Venera and Pioneer Venus descent probes show that the Venus atmosphere below the main cloud deck is 'clear'. However, it should be recognized that this may be a somewhat relative term – the dynamic range of the instrumentation used is modest, and the fact that there is already so much opacity above 40km makes radiative-convective models somewhat insensitive to the introduction of dust in the lower atmosphere. Both Pioneer Venus and Venera measurements show variations in opacity in the lowest few kilometers – implying, perhaps, sources and sinks. Recently, Venera -13 and -14 electrical data have been suggested to be consistent with the presence of charged aerosols in the lowest 40km of the atmosphere (Lorenz, 2018).

It is striking that out of only two occasions (Venera 13 and 14) when multiple panoramas were taken at a landing site in the space of about an hour, sand and dust were observed to move. Such an event might typically take months or years to observe on Earth, Mars or Titan! It can therefore be argued (Lorenz, 2015) that surface windspeeds on Venus not infrequently exceed the transport (saltation) threshold and the possibility exists that surface dust-lifting may be common. Additionally, there is the prospect of injection of volcanic ash into the atmosphere. Some of these processes may also be associated with electrical activity. Compared to Earth and Mars, the effectiveness of snow-out or rain-out processes on Venus will be poor.

The possible dust generation, injection and removal processes on Venus will be reviewed and the extent and character of lower atmospheric dust considered. In-situ measurements (optical and/or electrical) on future missions will be needed to resolve the question.

Session 12

Future Missions

Solar Spectrum and Intensity Analysis Under Venus Atmosphere Conditions for Photovoltaics Operation

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Solar Spectrum and Intensity at Venus is significantly different from Earth. Due to its thick sulfuric acid clouds, solar illumination at Venus is very weak, altitude dependent and diffused. This analysis uses measured solar spectrum from Venera 11 [1] and Venera 13 [2] missions (Figure 1a). Venera 11 entered the Venus atmosphere at -14 degrees latitude at 11:10 AM local solar time (solar zenith angle 37°) and descended to the surface of Venus. Venera 13 entered the Venus atmosphere at -7.5 degrees latitude at 9:27 AM local solar time (solar zenith angle 38°) and descended to the surface of Venus [3]. Current solar cells do not function effectively in Venus aerial and surface environments, and are not suitable for long-duration Venus aerial missions. This work is focused on the development of solar power system technologies required for mid/low altitude Venus exploration mission concepts. Venus variable altitude (mid- to surface level) missions would require solar power systems that can operate at high temperature (200-350°C) for long duration, survive at 465°C Venus surface environment for short duration and generate power under 100-300 W/m^2 solar irradiance conditions. Based on Venera 11 descent probe measurement, we propose to develop solar cells as depicted in Figure 1b that can generate power for Venus aerial missions. Although current III-V multi-junction solar cells are typically designed to operate under AM1.5 or AM0 solar spectrum, the objective here is to design a solar cell structure that is optimized for Venus red-shifted solar spectrum. High temperature Current-Voltage (IV) and external quantum efficiency (EQE) measurements under Venus conditions will be presented (Figure 1c).

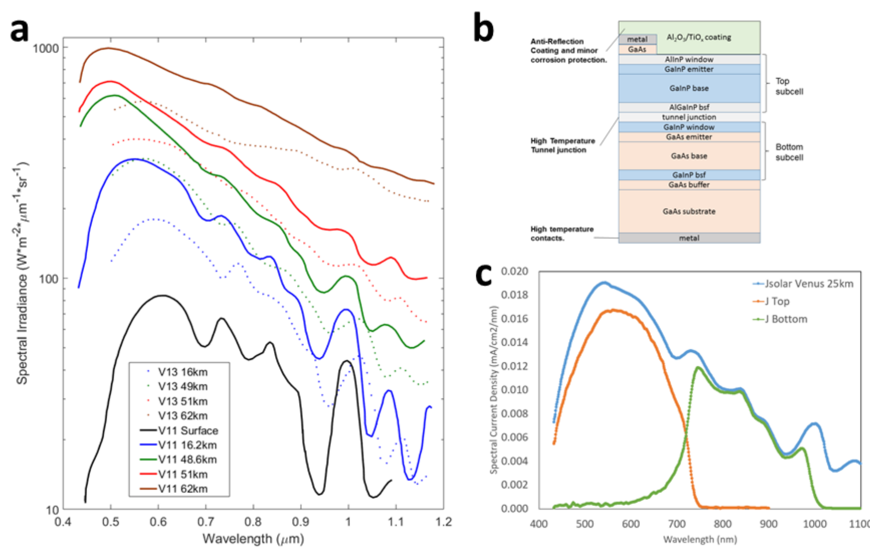

Fig. 1. (a) Solar spectra of the downward scattered solar radiation measured by the Venera 11 and Venera 13 descent probes. (b) Simplified cross-section schematic of a GaInP/GaAs 2J solar cell designed for Venus solar and high temperature operation. Calculated current density in the GaInP (3.90 mA/cm^2) and GaAs (2.42 mA/cm^2) subcells for the 300°C EQE data using the Venus solar spectrum at 25 km altitude where temperature is 300°C.

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Venus Airglow Measurements and Orbiter for Seismicity (VAMOS): A SmallSat Mission Concept Study

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The planetary evolution of Venus remains elusive half a century after the first visit by a robotic spacecraft. It is necessary to detect the signs of seismic activity to get better understanding of how Venus evolved. Adverse surface conditions exist on Venus including extremely high temperature and pressure on the surface and it is infeasible with current technologies to place seismometers on the surface for an extended period of time. Thanks to dynamic coupling between the solid planet and the atmosphere, the waves generated by quakes propagate and can be detected in the atmosphere itself.

The Venus Airglow Measurements and Orbiter for Seismicity (VAMOS) is a mission architecture concept to enable a SmallSat in Venus orbit to detect and assess fluctuations in the neutral atmosphere and ionosphere induced by seismic waves. Venus is surrounded by the brightest naturally occurring airglow known in the Solar System. At high altitudes in the atmosphere, on the day-side of Venus, the strong flux of ultraviolet radiation coming from the Sun ‘breaks’ the molecules of carbon dioxide (‘CO2’) present in large quantities in the atmosphere, generating free oxygen atoms. Oxygen atoms are then transported to the nightside where they recombine during descent. The newly formed molecular oxygen emits radiation to produce airglow. We can observe localized and short-lived regions of emission and neighboring dark areas demonstrating the potential of using such observations to monitor seismic activities.

In our investigations, we model both the 1.27 µm nightglow and the dayside 4.28 µm non-local thermodynamics equilibrium (non-LTE) signals associated with the waves. The results indicate that the detection threshold for the VAMOS imager expected performances is Ms 6 for 1.27 µm and Ms 5 for 4.28 µm. With the expected level of seismicity of Venus (~25 times less than Earth) and about half these quakes occurring on the nightside of VAMOS, this might provide us about 2 and 25 detections per year, including 5 detections or more with wave detection strong enough to allow regional studies of crustal thickness including investigating various regions on Venus such as lowlands, highlands, and Tesserae.

In summary, the VAMOS mission concept is investigated at JPL as part of the NASA Planetary Science Deep Space SmallSat Studies (PSDS3) program, which can produce a viable and exciting mission concept for a Venus SmallSat. In addition, it will have the opportunity to examine many issues facing the development of SmallSats for planetary exploration. Our mission concept VAMOS would measure perturbations in the atmosphere from an orbiting platform that could provide a critical breakthrough in detecting seismicity on Venus and in the monitoring of seismic wave propagation.

Exploration of Venus with Aerial Platforms : J. A. Cutts* , J. L. Hall, L. H. Matthies and T. W. Thompson, [1]Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive Pasadena, CA 91109, James.A.Cutts@jpl.nasa.gov.

The Venus Aerial Platform Study, sponsored by NASA's Planetary Science Division, is examining alternative approaches for exploring Venus with aerial vehicles in order to develop a Venus Aerial Platform Roadmap for the future exploration of the planet. Two Study Team meetings were conducted in May and December of 2017: the first focused on the scientific opportunities offered by aerial platforms at Venus, while the second meeting examined the technologies needed for operating in the severe Venus environment. More than 60 scientists and engineers have been involved in the study. The final report is expected to be issued in May 2018. This abstract describes the preliminary findings of the study.

Aerial Platform concepts examined include vehicles which operate at a single fixed altitude, have the ability to change altitude, and have full three dimensional mobility. In general, enhanced mobility requires additional mass for the power and propulsion systems which has the inevitable consequence of lower payload mass fraction given the same instrumentation suite. For all concepts, payload fractional percentiles as a function of launch mass are in the single digits. The study found that variable altitude concepts represented a sweet spot offering much more science than a fixed altitude platform yet avoiding the high complexity and low payload fractions of platforms with full three dimensional mobility. While developing these key mobility technologies is paramount, the study also found that there are other capabilities vital to the scientific productivity of an aerial platform mission are including navigation and localization, relay telecommunications of data, and miniature scientific instruments. .

NASA is currently considering a collaboration with Russia and the Venera D mission in which NASA would furnish an aerial platform. NASA is also examining the feasibility of a program of low cost Venus missions termed Venus Bridge which would include potential balloon mission. Concepts applicable to both classes of opportunity will be discussed.

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HIGH-ALTITUDE SOUNDING OF THE INTERIOR OF VENUS: STRATOSPHERIC BALLOON TEST R.E. Grimm, Southwest Research Institute, 1050 Walnut St. #300, Boulder, CO 80302 (grimm@boulder.swri.edu).

Introduction. Electromagnetic (EM) sounding uses induction from natural sources to build profiles of electrical conductivity (or resistivity) of planetary interiors, which in turn can be translated to temperature and composition. Theory indicates that measurements of transverse electromagnetic (TEM) waves—in particular, lightning-caused global Schumann resonances—at any altitude in the ground-ionosphere waveguide contain information on the resistivity structure of the boundaries (Grimm et al., Icarus, 217, 462, 2014). In other words, aerial measurements can be used to probe the subsurface. This technique can measure geothermal gradient and hence lithospheric thickness of Venus from a nominal 55-km balloon float altitude, and thus make a fundamental contribution to understanding the geodynamics and interior structure of Venus without ever touching the surface.

Balloon Transverse Electromagntic Measurement (BTEM). An experiment measuring AC electric and magnetic fields flew over the Idaho's Salmon River Mountains in October, 2017 (Fig. 1). The objectives were to (1) demonstrate that the TEM band can characterized in the stratosphere. (2) demonstrate that electric fields follow lossy waveguide theory. (3) determine simultaneously the frequency dependent electrical conductivities of the ground and ionosphere. (4) determine the requirements to advance to TRL 6 for Venus flight. Results of the initial flight confirmed that the ground and ionosphere were sensed with correct order-of-magnitude resistivities (Fig. 2). A follow-up night flight in Oct 2018 will test different ionospheric conditions.

Fig. 1. BTEM in flight near Butte, MT, USA. Electric fields are measured between boom-tip electrodes (4-m separation); magnetometers are inside booms. Payload is spatially and electrically isolated from balloon avionics (teal cable in foreground is fiber-optic connector).

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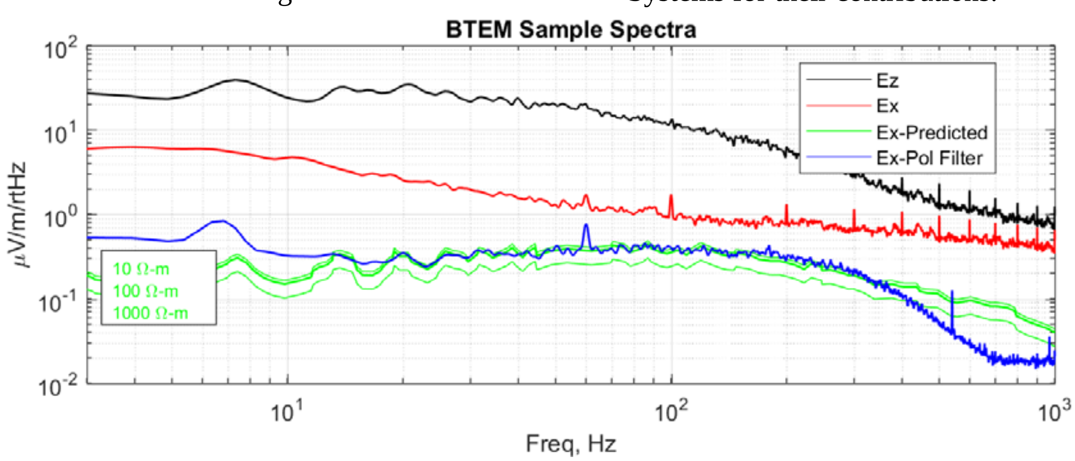

Figure 2: Analysis of 1 minute of data at float altitude 33 km. Large vertical (black) electric field is the primary and small horizontal (red) electric field is the secondary. Polarization filter drastically reduced coherent noise from air-traffic control transponder on the balloon avionics (blue). Predicted signal (green) using nominal quiet-day ionosphere is constent with ground resistivity 10-100 Ω-m.

The geologic study of Imdr Regio as an opportunity to observe active volcanism on Venus in the perspective of future missions

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Orbital observations from the ESA Venus Express mission indicated 1 μm emissivity anomalies over the summit and eastern flank of Idunn Mons [1,2], a 200 km diameter volcano situated in Imdr Regio, a volcano-dominated large topographic rise on Venus. The observed emissivity anomalies are typical of poorly weathered deposits and – for this reason – may be indicative of geologically recent and possibly current ongoing volcanic activity [1,2].

Using the dataset of the NASA Magellan mission, we are performing a detailed geologic study of Imdr Regio and Idunn Mons. Preliminary observations of the tectonic setting around Idunn Mons suggest a complex interaction between the local stress fields associated with the formation of the volcano and the regional stress fields associated with the formation of Olapa Chasma, the rift zone within which Idunn Mons rises. The tectonomagmatic processes behind the formation of Idunn Mons and Olapa Chasma are likely contemporaneous, a fact that is confirmed by the characteristic "hourglass" pattern of radial fractures and grabens around the volcano [3]. The relationship of this radial suite of fractures with the Idunn Mons lava flows and with the fractures associated with Olapa Chasma will be constrained as part of the current geological study.

The summit of Idunn mons is characterized by approximately flat topography, and multiple caldera collapses, which could be related to multiple flow events. Stratigraphic interpretation and morphometric analysis of the lava flows associated with Idunn Mons will provide more detail about the eruptive style of this large volcano. In fact, through analysis of the eruptive style of the volcanic structure, we can infer important clues about the local subsurface volatile content. The volatile content, in turn, has a direct impact on the rheological properties of the mantle and can potentially reveal whether or not a localized asthenospheric layer can exist beneath Imdr Regio. Hence, the geologic study of Imdr Regio is key to resolving the debate regarding whether Venus experienced catastrophic or equilibrium volcanic resurfacing.

Mission concepts for future exploration of Venus are currently being proposed, which involve both in-situ geochemical analyses performed by landers [4,5] and the detection of Venus-quakes associated with volcanic eruptions [6]. Imdr Regio is a perfect laboratory of analysis for these concept proposals and the geologic mapping of this region will provide the necessary information to select the local areas to be targeted by these future missions.

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Preparing for Venus Surface Exploration

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Exploration of the Venus surface and deep atmosphere to better understand terrestrial planets, including Earth, has been a long-standing objective of the Venus science community. However, the hostile environmental conditions at the surface coupled with thick acidic clouds and dense atmosphere have made achieving those objectives challenging. Previous landers survived only about 2 hours [1] limiting our knowledge of the constituents and processes near the surface. Remote sensing data in this region is generally limited to Magellan radar data, and coarse imaging at 1 micron windows [2-7]. NASA has begun to undertake steps to overcome the challenges and prepare to explore this complex and relevant region of Venus. For example, recent technology advances in sensors, electronics, power and other systems have been funded and this, combined with the new capabilities to replicate Venus conditions on Earth, are changing this paradigm.

One recent new capability is a facility that's capable of replicating Venus atmospheric conditions with high fidelity at essentially any altitude from the surface up to about 75 km. This facility, the Glenn Extreme Environment Rig (GEER), located at NASA's Glenn Research Center, is the largest volume and most comprehensive simulation capability known. GEER can replicate temperature and pressure conditions and, perhaps most uniquely, has the ability to create and indefinitely maintain relevant chemistry. This capability has been demonstrated in numerous tests, several of them lasting 60 days or longer. These successful tests have included Venus geological experiments [8], exposure tests for technology development efforts [9], material compatibility tests [10], and tests to support sensors and instrument developments. As will be presented by Lebonnois et al, at this conference, little is understood about the deepest atmosphere of Venus [e.g. 11]. Given the new capability of GEER, the time is right to begin to experimentally explore the supercritical nature of this environment.

NASA has also begun development of a long lived Venus surface station. This project, called LLISSE (Long-Lived In-situ Solar System Explorer), is utilizing high temperature electronics and systems to develop a lander that can reliably operate on Venus for an extended period of time, in this case for at least 60 days! [12]. This long lived lander will begin tackling temporal science of the deep Venus region, something never before attempted. If successful and flown, LLISSE will provide insight into the atmospheric dynamic processes and perhaps the super rotation phenomena. The current state of LLISSE will be discussed.

Further, NASA is investing in mission concept studies to help refine our plans and identify where critical investments are needed. One recent stud is SAEVe (Seismic and Atmospheric Exploration of Venus) [13]. It explored what a mission designed around core LLISSE capabilities may be able to achieve if mass is not limited to 10 kg as originally scoped. The study showed that a pair of Venus landers designed to operate for a full Venus solar day could be implemented for an estimated cost of $100M US and stay within a "small sat"category. This mission concept will be presented.

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DEVELOPMENT OF THE VENERA-D MISSION CONCEPT, FROM SCIENCE OBJECTIVES TO MISSION ARCITECTURE.*L. Zasova[1], L. Glaze[2], A. Burdanov[3], T. Economou[4], N. Eismont[2], M. Gerasimov[2], D. Gorinov[2], J. Hall[5], N. Ignatiev[2], M. Ivanov[6], K. Lea Jessup[7], I. Khatuntsev[2], O. Korablev[2], T. Kremic[8], S. Limaye[9], I. Lomakin[10], M. Martynov[10], A. Ocampo[11], S. Teselkin[10], O. Vaisberg[2], V. Voronstsov[10]. [1]*Space Research Institute RAS, Russia,* [2]*NASA Goddard Spaceflight Center, USA,* [3]*TSNIIMASH, Russia,* [4]*Enrico Fermi Institute, USA,* [5]*Jet Propulsion Laboratory, USA,* [6]*Vernadsky Inst. RAS, Russia,* [7]*Southwest Research Institute, USA,* [8]*NASA Glenn Research Center, USA,* [9]*Univ. of Wisconsin, USA,* [10]*Lavochkin Assoc., Russia,* [11]*NASA Headquarters, USA,.*

Background: Building on the results of the highly successful Soviet Venera and VEGA missions [1], along with the Pioneer, Magellan [2,3], and more recent Venus Express and Akatsuki missions [4,5], a joint NASA-IKI/Roscosmos Science Definition Team (JSDT) was established in 2015. Within the overarching goal of understanding why Venus and the Earth took divergent evolutionary paths, the JSDT has the task of defining the science and architecture of a comprehensive Venera-D (Venera-Dolgozhivuschaya (long-lasting)) mission. The baseline Venera-D concept includes two elements, orbiter and a lander, with potential contributions consisting of an aerial platform/balloon, small long-lived surface stations, (LLISSE) or a sub-satellite. LLISSE is studied to be included as a Lander payload element even in baseline concept. In January of 2017, the JSDT completed the first phase and generated a report to NASA - IKI/Roscosmos of its findings [6]. The second phase of the JSDT activities is currently underway with a focus on refining the science investigations, undertaking a compressive development of the core orbiter and Lander mission architecture, a detailed examination of contributed elements and aerial platforms that could address key Venus science [7, 8]

Venera-D science goals: Venera-D investigations would address the dynamics of the atmosphere with emphasis on atmospheric superrotation, the origin and evolution of the atmosphere, and the geological processes that have formed and modified the surface with emphasis on the mineralogical and elemental composition of surface materials, and the chemical processes related to the interaction of the surface and the atmosphere and thesolar wind and plasma environment.

Venera-D mission concept architecture: JSDT members from Lavochkin Association are leading the mission concept architecture development [6]. This assessment includes: (1) Development of the general configuration for both the orbiter and the lander; (2) Accommodation of systems and subsystems within the orbiter and lander; (3) Assessment of orbit options along with the strategy for descent and landing and long term observation of LLISSE; (4) Evaluation of telecommunication options from the spacecraft to Earth and from the lander and LLISSEto the orbiter; (5) Accommodation of an aerial vehicle in its own delivery system. Launch dates between 2026 and 2031 have been evaluated.

Venus Aerial Platforms: The JSDT concluded that *in situ* atmospheric measurements over an extended period of time (days to months) would be scientifically enabling. Thus, a high priority augmentation to the core concept would be an aerial platform to address science focused on atmospheric superrotation, chemistry, and trace species in the middle cloud layer.

Ongoing activities of the Venera-D JSDT: The current phase of activity of the Venera-D JSDT will result in a report to be delivered to NASA-IKI/Roscosmos in late January of 2019. The tasks of the group will concentrate on (1)science refinement and evaluation of payload elements, specifically notional instruments; (2) development and refinement of the mission concept architecture including mission operations and risk assessment; (3) evaluation of potential landing sites within the context of the evolving lander engineering concept; and (4) incorporation of the results from the aerial platform study in the evaluation of a potential contributed element(s).

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Session 06

Poster (1)

Experimental investigation of wet atmosphere-surface interaction at the conditions of Venus surface: an example for early terrestrial planets.

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Introduction: Modern Venus is considered as a warm and dry planet. The low dielectric constant of the deep atmosphere precludes significant alteration today, except the formation of iron oxide on Fe-bearing minerals [1] and a global sulfurization of the surface [2,3]. Several hypotheses of atmospheric H_2O content variation with time ranged from a rapid early decline to a sporadic decline associated to sporadic influx from recent volcanism [4]. The aim of this study addresses the mineral transformation under a wet supercritical atmosphere in the CO_2-H_2O-S(trace) system, in continuation of [5]. We focused on the reaction rates monitored by the thickness of the alteration layer at the surface of tested materials exposed to the wet, low density, supercritical fluid at 470°C and 9 to 60 MPa.

Experimental Details: The experiments were conducted at 470°C in a 320 ml reactor made of a Ni-based alloy preventing corrosion and buffering the redox conditions closed to the present Venus deep atmosphere. The CO_2-based gas, initially at 9 MPa, contained 3.5% N_2, 130 ppm SO_2, 15 ppm CO and trace of H_2S. Various concentrations of H_2O were tested by injection of appropriated amount of water, up to 60 MPa. Various silicate samples were exposed to alteration. The results focused on glassy materials, the alteration kinetics of which allowing accurate measurements in reasonable experimental time: a natural pumice, a synthetic basalt glass and a natural obsidian. The mineral transformations of the investigated samples were analyzed by scanning electron microscopy (SEM) and X-ray diffraction (XRD). The typical duration of the experiments was 1 week. Few runs were conducted for 1 day and 1 month to investigate the effect of time at constant water pressure.

Results: The alteration process differs from one glass to another. Obsidian recrystallized into an anorthoclase-hornblende assemblage. Basalt glass developed a chemically leached inner layer covered by a chlorite-sulfate enriched outer layer. Pumice, a porous material, fully recrystallized under the higher H_2O pressure. Examples are given in Fig.1.

Discussion and concluding remarks: The fugacity of water in each run was calculated with available Equation of State programs. Obsidian is used as a reference material here. The thickness of its alteration layer increased with fH_2O as showed in Fig.2. The data are processed through the Transition State Theory and a shrinking core model to take into account the surface reaction combined with diffusion processes. We proposed a method to extrapolate to supercritical conditions the kinetic laws established for minerals and glasses at lower temperature in condensed fluids. Although the short duration of the experiments makes speculative the extrapolation to the whole geologic history of Venus, we offer new insights to possible processes having affected the surface of this planet as well other terrestrial planets dominated by hot CO_2-H_2O atmosphere during their early history.

Fig.1: SEM observations and XRD pattern of altered obsidian (right) and basalt glass (left)

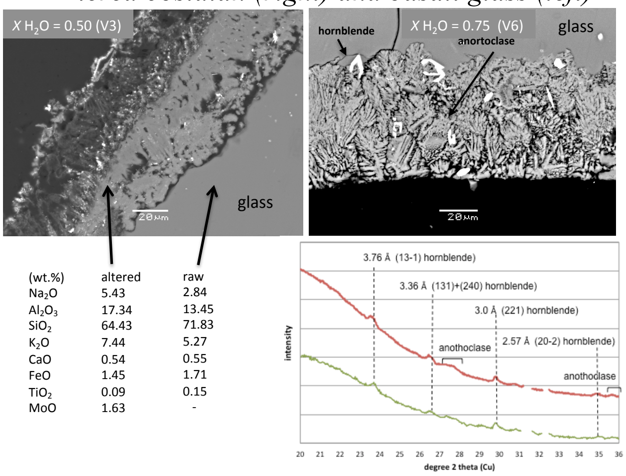
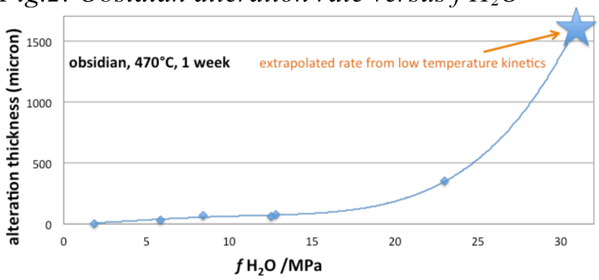


Fig.2: Obsidian alteration rate versus f H2O



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PROSPECTS FOR THE INVESTIGATION OF VENUS' INTERIOR USING INFRASOUND

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With surface temperature and pressure as high as 450 C and 90 atmospheres respectively, Venus presents a formidable challenge to any missions that aim to perform conventional seismology. However, Venus' dense atmosphere offers unique opportunities for performing remote seismology using sensors deployed on a balloon platform in the mid-atmosphere. Earth-like temperature and pressure at 50-60 km altitude allow for mission lifetimes to be much longer than those of surface landers.

In this presentation, we will explore the possibility of mapping seismic activity on Venus, including quakes and volcanic eruptions using infrasound (pressure waves with frequencies less than 20 Hz) as a remote sensing tool and discuss the progress our group has made in the last year towards this goal.

The efficiency of infrasound generation from seismic activity relies heavily on the coupling between the solid planet and the atmosphere. The dense atmosphere on Venus couples ground motion signals up to 60 times more efficiently into the atmosphere, generating infrasound signals that may be detected by pressure sensors floating on balloons in the mid atmosphere. Further, acoustic sensors used to capture infrasound may also be used to investigate low-frequency, large-scale planetary atmospheric features such as planetary-scale gravity waves, which have recently been observed by JAXA's Akatsuki mission.

Our team has been involved in a campaign to use the Earth's atmosphere as an analog testbed for Venus to demonstrate the feasibility of balloon-based infrasound science on Venus and address the challenges associated with it. While infrasound has been recorded from seismic events such as quakes and volcanic eruptions on Earth by terrestrial stations, its detection from balloon platforms is a relatively new area of research. In recent experiments, we demonstrated that infrasound signals from weak artificially created earthquakes could be detected by barometers suspended from balloons. Further, we have also shown the detection of infrasound from rocket launches over 200 km away. These experiments are helping us address strategic knowledge gaps, which would allow for the detection and characterization of seismic infrasound on Venus. Results from the above campaign activities will be summarized in our presentation.

In the future, we look forward to conducting campaigns to detect and characterize infrasonic signals in the Earth's stratosphere – the closest analog to what we would expect in Venus' atmosphere at 55-60 km altitude. Proving the feasibility of this technology in the Earth's stratosphere would make a strong case for the detection of similar signals on Venus, which would pave the way for the study of its interior, a long-cherished goal of the Venus community.

Are the steep-sided domes produced of non-basaltic lava?

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Geologic analysis of the Venera 15/16 and Magellan radar images of Venus [1, 2], supported by the *in situ* identification of chemical compositions of the Venusian surface material by the Venera 9, 10, 13, 14 and Vega 1, 2 landers [3] showed that at $\sim$ 0.5 – 1 Ga ago intensive basaltic volcanism in the form of volcanic plains and gentle-sloping shield volcanoes was a major factor of geologic activity on this planet. Subsequently its intensity significantly decreased, but at some localities evidences of still ongoing volcanic eruptions are observed [4].

The radar images of the Venusian surface revealed amid the basaltic plains and shield volcanoes more than a hundred of distinctive steep-sided domes (SSDs) [5], which morphology is rather similar to that of andesitic, dacitic or rhyolitic domes on Earth, suggesting that the Venusian SSDs were formed by eruptions of viscous lavas. Another possibility of their formation is eruptions of foamy (and thus viscous) basaltic lavas whose presence on Venus may be supported by high ($\sim$ 100 bar) atmospheric pressure [5]. Other discussed possibilities of the SSDs formation are the low-eruption rate discharge of basaltic lavas [6] and eruptions of significantly crystallized (and thus viscous) also basaltic lavas [7]. The question of the SSD's composition is therefore important for understanding whether the Venusian volcanism was essentially basaltic or more differentiated magmas were also produced. In the latter case mechanism(s) of formation of the differentiated magmas should be considered.

Imaging the surface in the near-infrared (NIR) through the "transparency windows" is the only available to date method for sensing mineralogical composition (apart from the site-limited *in situ* measurements). The Venus Monitoring Camera (VMC), whose data were used in this work, was imaging the surface during 2 006 – 2 014 from the board of Venus Express spacecraft through 1.01 μm transparency window. The NIR images of the surface are blurred due to scattering in the atmosphere and clouds, that limits their spatial resolution to $\sim$ 100 km, but some SSDs are large enough to be clearly resolved in available NIR images. For this work we selected a number of SSDs from the catalog [5] which are reasonably well covered by the VMC observations. For the selected areas we computed model NIR emissivity for the domes and statistically compared mean emissivity values between the SSDs and surrounding basaltic plains following the method from our previous works [*e.g.*, 8]. We will present results of the comparisons and the geologic interpretations of the findings.

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Although convection has been suggested to occur in the lower part of Venus' cloud layer by some observational evidences, its structure remains to be clarified. In the previous studies, Baker et al (1998, 2000) and Imamura et al (2014) try to simulate Venus' cloud-level convection, but the model they utilized is two-dimensional. Lefevre et al (2017) also perform a three-dimensional simulation using only similar settings of Imamura et al (2014). However, a three-dimensional numerical calculation using similar settings of Baker et al has not been performed yet. Here we report on the results of our numerical simulations performed in order to investigate a possible three-dimensional structure of Venus' cloud-level convection using similar settings of both Baker's and Imamura's.

We use the convection resolving model developed by Sugiyama et al. (2009). The model is based on the quasi-compressible system (Klemp and Wilhelmson, 1978), and is used in the simulations of the atmospheric convections of Jupiter (Sugiyama et al., 2011, 2014) and Mars (Yamashita et al. 2017). We perform two experiments. The first one, which we call Ext.B, is based on Baker et al. (1998). A constant turbulent mixing coefficient is used in the whole computational domain, and a constant heat flux is given at the upper and lower boundaries as a substitute for radiative forcing. The second one, which we call Exp.I, is based on Imamura et al. (2014). The sub-grid turbulence process is implemented by Klemp and Wilhelmson (1989), and an infrared heating profile obtained in a radiative-convective equilibrium calculation (Ikeda, 2011) is used. In both of the experiments, the temporally averaged solar heating profile is used. The spatial resolution is 200 m in the horizontal direction and 125 m in the vertical direction. The domain covers 128 km x 128 km horizontally and altitudes from 40 km to 60 km. The horizontal domain size is set to be larger than that employed in Lefevre et al (2017) in order to permit the excitation of larger scale gravity waves.

In our poster, we will discuss the difference of convective motions and heat budgets obtained in Exp.B and Exp.I. We will also show the propagation of gravity wave driven by convection.

Composition and clouds, some insights and questions from the coupled IPSL Venus GCM.

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We have coupled new codes of photochemistry and microphysics to the LMD general circulation model of Venus (Lebonnois et al., 2016). The photochemical package is based on our photochemical model already in use for Mars (e.g., Lefèvre et al., 2008). The model provides a comprehensive description of the CO_2, sulfur, chlorine, oxygen, and hydrogen chemistries with state-of-the-art kinetics data. It also includes a simplified treatment of cloud microphysics that computes the composition, number density, and sedimentation rates of sulfuric acid aerosols based on observed altitude-dependent size distributions. We will describe the results obtained with this first three-dimensional model of the Venus photochemistry. The space and time distribution of key chemical species will be discussed and compared to observations performed from Venus Express and from the Earth. We will place particular emphasis on SO_2, which is subject in the GCM to three-dimensional transport, convective mixing, condensation-evaporation-sedimentation via H_2SO_4 in the cloud layer, and photochemistry above the clouds.

In addition to the photochemical code, which only contains a simplified microphysics, we have developed a comprehensive microphysical scheme: The Modal Aerosol Dynamics of Venusian Liquid Aerosol cloud model (MAD-VenLA) uses an implicit moment scheme to describe the particle size distribution and the microphysical processes in 0D. The particle size distribution is assumed to be log-normal and is described by two moments: total particle number (zeroth moment) and total particle volume (third moment) of the size distribution (Seigneur et al. 1986, Burgalat et al. 2014). This 0D model has been tested against a reference model (SALSA, Kokkola et al. 2008). We have developed a 1D extension to our model to be able to represent a source of aerosol particles that can act as condensation nuclei and to be able to calculate the sedimentation of our cloud droplets. We are currently coupling MAD-VenLA with the 1D version of the IPSL Venus GCM and will be able to do 3D simulations in the future. This will enable detailed investigations on the coupling of cloud microphysics with atmospheric chemistry, and later on also with radiative transfer and dynamics.

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The global variation of Venus' clouds obtained from IR1 camera onboard AKATSUKI

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Venus is our nearest neighbor, and has a size very similar to the Earth's. However, previous observations discovered an extremely dense (92 bar at the surface) and CO_2-rich atmosphere, with H_2SO_4 thick clouds. The Venus cloud consists of H_2SO_4 main cloud deck at 47 – 70 km, with thinner hazes above and below. The upper haze on Venus lies above the main cloud surrounding the planet, ranging from the top of the cloud (70 km) up to as high as 90 km.

Near infrared (0.986 um) dayside image of Venus has taken by solid state imaging (SSI) of the Galileo spacecraft (NASA). It appears almost flat, there are some small scale features with a contrast of 3 % [Belton et al., 1991]. In Takagi et al. (2011), it may be calculated that the source of the contrast of the order of 3 % in near infrared Venus dayside image is due to variation in the cloud optical thickness.

On December 7, 2015, AKATSUKI (JAXA) approached Venus and the Venus orbit insertion was successful. After the Venus orbit insertion, many 0.90 μm Venus dayside images were taken by the 1 μm near infrared camera (IR1) onboard AKATSUKI. In this study, cloud optical thickness variation are investigated from 0.90 μm Venus dayside images taken by IR1 camera and radiative transfer calculation globally. Further, meteorological some changes that contribute to cloud variation are examined. Furthermore, I will introduce observation plan in using PIRKA telescope of Hokkaido University.

Formation of planetary-scale ultraviolet contrast at the Venus' cloud top by horizontal material transport induced by planetary-scale waves and the mean circulation: analysis of VEx/VMC images

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Ultraviolet (UV) images of Venusian cloud top exhibit various planetary-scale features which reflect spatial variations in the amount of unidentified UV absorbers (Moroz et al., 1985; Mills et al., 2007). One of the significant features is the dark horizontal Y feature (e. g., Rossow et al., 1980), which is an equatorially symmetric dark pattern with a zonal wavenumber of unity accompanying tilted dark bands extending from the equator to high latitudes and a dark equatorial band at the root of the Y. Though the Y feature is frequently observed with some temporal variability in the structure, its generation mechanism has been unclear for more than 40 years since its discovery (Boyer and Guérin, 1969).

Del Genio and Rossow (1990) showed that the propagation of the equatorial UV contrast with a zonal wavenumber of unity tended to be faster than the mean zonal velocity based on the analysis of the cloud-tracked wind speed and the periodicity of the brightness. This suggests that planetary-scale waves propagating faster relative to the background wind are responsible for the Y feature. To understand the role of spatially and temporally varying winds in the formation of the Y feature, comparison between the cloud morphology and the wind field is essential.

In this study, the relationship between the planetary-scale UV contrast known as the Y feature and the wind field at the Venusian cloud top was investigated by using images obtained by Venus Monitoring Camera (VMC). Spectral analyses for temporal variations of the UV reflectivity and the wind field revealed periodicities of 4-5 Earth days, which would be attributed to Kelvin and Rossby waves with a zonal wavenumber of unity. Based on the morphological relationship between the dark streaks and the enhancement of poleward flow, we propose a mechanism for the formation of the Y feature: dark materials are supplied to the cloud top in the equatorial region by a Kelvin wave, subsequently advected poleward by the mean meridional circulation and a Rossby wave, and then stretched by the mid-latitude jet to form the tilted band structures. A simplified transport model was developed to demonstrate the scenario.

Periodic analysis of the limb darkening in Venus' thermal images taken by Akatsuki LIR

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The mechanism of Venus' strong zonal wind blowing at 60 times the speed of its rotation, called the super-rotation, is still unclear. Various waves of planetary scale have been proposed as the cause of the super-rotation, but it has not been elucidated yet.

Planetary-scale waves are known to exist in the atmosphere of Venus. For example, periodic fluctuations with periods of 4 to 5 days in UV brightness were discovered at the cloud top by Pioneer Venus orbiter (DelGenio and Rossow1990). Analyses of velocity fields obtained by cloud tracking revealed that zonal and meridional winds also fluctuate with periods of 4 to 5 days (Rossow et al. 1990; Kouyama et al. 2012, 2015). It has been clarified that various waves exist on Venus, but their spatial structures are not well understood. We focus on the periodical fluctuation of the cloud top temperature which has not been studied well.

We used images taken by the Long Infrared camera (LIR) onboard JAXA's Venus orbiter Akatsuki. LIR can capture the temperature of clouds around 65 km altitude. The image data taken by LIR has a systematic error of ~3K and a relative error of ~0.3K. Thanks to the small relative error of LIR, comparison of brightness temperatures in each image can be relatively accurate, and thus spatial inhomogeneities of the brightness temperature caused by waves are expected to be detectable. We focus on limb darkening, which reflects the vertical gradient of the atmospheric temperature.

The magnitude of the limb darkening at different latitudes are evaluated as follows. We first extract brightness temperatures at a specific latitude from each image in the Level-3x data product of LIR. Then, using least squares method, a straight line is fitted to the brightness temperature as a function of the emission angle in the emission angle range of 60° -90° ; the slope of the fitted line represents the magnitude of limb darkening. This procedure is repeated for multiple images acquired successively, and the obtained time series of the slope is analyzed to extract periodic variations. We carried out this analysis for different latitudes from the equator to the high latitude using data taken in successive 20 days, and found that there exist periodic fluctuations with periods of 4 to 5 days at all latitudes.

Several waves are thought to affect the periodic fluctuations detected in this analysis. We will analyze the data for a longer period of time and try to separate the wave components by spectral analysis.

Title:
Venus glory: A key to understand cloud aerosols' properties and absorptions using images

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Abstract:
Glory is an optical phenomenon generating a local maximum of reflected solar radiance at small phase angles (the angle of the Sun, Venus, and an instrument). This holds clues on microphysical properties of cloud aerosols, such as size distribution, owing to their strong influences on the phase angle dependency of scattered solar radiance. Glory was observed with the Venus Monitoring Camera (VMC) onboard Venus Express (2006-2014) and extensively analyzed [1-4].

The same phenomenon has been noticed also by UV Imager (UVI) onboard Akatsuki at its two channels; 283 nm and 365 nm [5]. Clear glory features are observed in the UVI images taken far away from the planet. Assuming 75% H_2SO_4-H_2O compositions for refractive index of cloud aerosols, we fit our model calculations to the observed phase angle dependence of global mean UV albedo. The results suggested the best-fit model with r_{eff}=1.26 μm and v_{eff}=0.076, while preferred least abundance of mode 1 aerosol [5]. However, there was a limitation to understand vertical distributions of the UV absorbers, such as SO_2 gas and an unidentified absorber, showing their maximum absorptions around 280 and 340-380 nm, respectively.

For better understanding on cloud aerosols' properties, we made close-up glory observations on October 27 and November 29 2017, and plan to make more in June-September 2018. These observations will provide about six times of glory observations along different latitudes. These future observations will use 283 nm, which will provide first close-up glory images in the Venus observation history.

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Retrieval of upper haze aerosol properties from SPICAV-UV and -IR data

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Introduction. Venus is covered by a thick layer of clouds extending from 40 to 70 km with tenuous upper haze layer lying above. Particles at the cloud top are spherical and consist of sulfuric acid droplets [1]. Clouds are stratified into three layers, the upper cloud region is populated by mode 1 (~0.2 μm) and mode 2 (~1 μm) particles. Before Venus Express, the upper haze was believed to consist of only mode 1 [1].

Early independent study of three channels of SPICAV/SOIR instrument with data set from three selected orbits showed presence of bimodality in size distribution [2]. Analysis of aerosol properties from single SPICAV−IR spectrometer for the whole data set obtained from May 2006 till November 2014 has proved it [3]. In this work, we report retrieval of upper haze aerosol properties from SPICAV−UV and –IR solar occultation observations for the whole data set.

Observations. 71 simultaneous solar occultation observations from SPICAV−UV and −IR instruments were processed from orbit #339 (February 2008) to #2464 (April 2011). Aerosol properties are determined using 6 wavelengths in 200−300 nm range from SPICAV−UV and 10 wavelengths in 650−1550 nm range for SPICAV−IR.

Method of analysis. The first step in retrieval procedure is calculation of aerosol extinction. Inversion method for SPICAV−UV is identical to the one used for SO_2 abundance retrievals [4]. Aerosol extinction retrieval of SPICAV−IR data was described in [3].

The second step is retrieval of particle size distribution by fitting spectral dependence of experimental normalized aerosol extinctions to their corresponding theoretical values. The aerosol extinction is modeled according to Mie theory, adopting refractive indices for 75% H_2SO_4 sulfuric acid aqueous solution. In our retrieval procedure unimodal and bimodal lognormal size distributions were considered independently.

The final step is to calculate aerosol number density as a ratio of experimental extinction coefficient to modeled extinction cross section.

Results. Examples of fitted normalized extinction at altitudes 89 and 92 km of orbit #444 are shown in Fig. 1. At 89 km, bimodality provides the best fit with effective radius r_{eff} = 0.13±0.02 μm and 0.81±0.1 μm and number density n = 13±3 cm^{-3} and (5.4±0.5)·10^{-3} cm^{-3} for mode 1 and mode 2 respectively. At 92 km, unimodal distribution is chosen with r_{eff} = 0.15±0.1 μm and n = 4±2 cm^{-3}.

Overall, aerosol size distributions have been retrieved at 127 altitudes from 71 solar occultation sessions mostly in the altitude range 86–96 km; bimodality has been observed 68 times most frequently in the altitude range 86–92 km, unimodality has been observed 59 times (Fig. 2c).

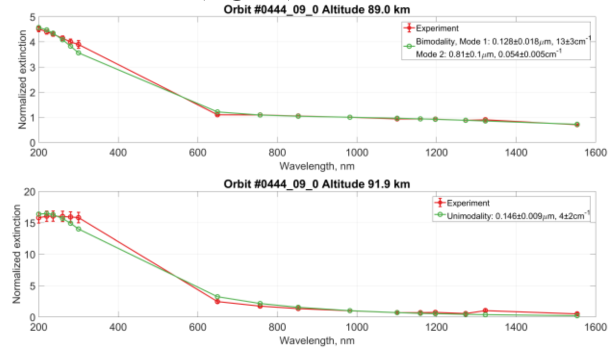

Fig. 1. Examples of fitted spectral dependence of aerosol extinction at altitudes 89 and 92 km of orbit #444.

All values of r_{eff} and n are averaged in 1 km altitude bins and plotted as vertical profiles in Fig. 2a and b. In addition, we have calculated mean values of r_{eff} and n for unimodal case in the whole altitude range (0.17±0.03 μm and 6±3 cm^{-3}) and for bimodal case in the 86–92 km altitude range (0.12±0.03 μm and 19±12 cm^{-3} for mode 1 and 0.7±0.2 μm and 0.09±0.05 cm^{-3} for mode 2).

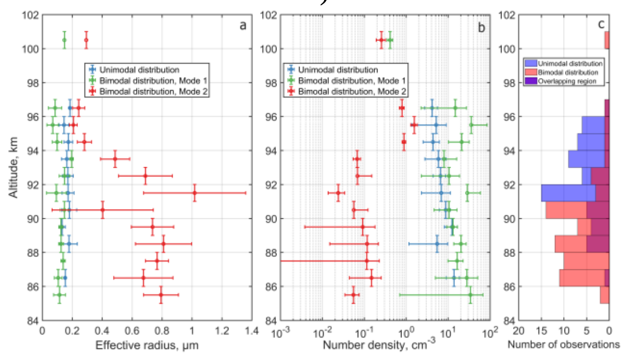

Fig. 2. Profiles of r_{eff} (a) and n (b) for unimodal and bimodal cases. (c) Altitude distribution of all observations.

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Radiative balances, horizontal distributions of clouds and large-scale effects of eddies revealed by a Venus General Circulation Model with radiatively-active clouds

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Abstract

We have developed a Venus General Circulation Model (VGCM) which takes cloud processes (condensation/evaporation, advection and gravitational sedimentation) and chemical processes related to sulfuric acid clouds/vapor and full radiative processes interactive with cloud distributions into account. The maximum zonal wind obtained is 110 m/s at middle latitudes and 70-75 km altitudes, which agrees with the observation from Pioneer Venus [Walterschied et al., 1986], successfully reproducing the superrotation. Also the model has suggested that SO_2 is lifted upward into the upper cloud layer in the equatorial atmosphere and changes into sulfuric acid clouds followed by a poleward transport along a meridional circulation [Kuroda et al., to be submitted].
In this presentation we show the simulated radiative balances of the atmosphere, horizontal distributions of clouds, and effects of eddies (thermal tides, transient waves, etc.) on the distributions. About 65 % of the incident solar flux is absorbed in the upper cloud layer, and then about 25 % in the lower cloud layer and atmosphere below the cloud layer. Consequently, 160 W/m^2 of the incident solar flux diminishes to 20 W/m^2 on the surface. This feature is in a good agreement with the observational result [Tomasko et al., 1980]. The apparent cloud top altitudes calculated with an optical thickness at 1.85-2.20μm are ~67 km altitude at the equator, ~65 km at mid-latitudes, and ~61 km at the pole (zonal averaged values). Calculating the optical thickness of SO_2 above the cloud top from the SO_2 mixing ratio, the “Y-feature” observed by UVI is reproduced around 65 km altitude. We also plan to show the comparisons of SO_2 distributions with observations by VEX/SPICAV and ground-based telescopes.

OBSERVATIONAL ANALYSIS OF VENUSIAN ATMOSPHERIC EQUATORIAL WAVES AND SUPERROTATION

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We investigate the dynamics of Venus's atmosphere in an attempt to link variability of atmospheric superrotation to the existence and occurrences of the Y-feature. The atmospheric superrotation, in which the equatorial atmosphere rotates with a period of approximately 4-5 days (~60 times faster than the solid planet) has forcing and maintenance mechanisms that remain to be explained. Temporal evolution of the zonal wind could reveal the transport of energy and momentum in or out of the equatorial region, and eventually shed light on mechanisms that maintain the Venusian superrotation. We postulate that the Y-feature is a manifestation of equatorial waves (either Kelvin, Rossby, or a combination of the two in nature) that may play a role in such energy transport that could affect Venus's superrotation. To understand the connection between the Y-feature and the superrotation, we must determine the frequency of Y-feature existence, the variability of the atmospheric wind field, and analyze the connection between the two to determine to what extent the Y-feature plays a role in Venus's superrotation.

We characterize the total and annual zonal mean wind fields of Venus between 2006 and 2013 in ultraviolet images captured by the Venus Monitoring Camera on board the ESA Venus Express (VEX) spacecraft which observed Venus's southern hemisphere. Our measurements show that, between 2006 and 2013, the westward wind speed at mid- to equatorial latitudes exhibit an increase of ~20 m/s. We also conduct ground-based observations, concurrent to observations by the Japanese spacecraft Akatsuki, with the 3.5 m Astrophysical Research Consortium telescope at the Apache Point Observatory (APO) in Sunspot, NM to extend our temporal coverage to present. Images we have captured at APO to date demonstrate that, even under unfavorable illumination, it is possible to see large features that could be used to confirm the Y-feature existence to later be compared to future wind analyses of Akatsuki images. The viability of tracking the existence of the Y-feature during VEX and Akatsuki is discussed and the analysis of such occurrences and wind field variability is ongoing. The APO observations additionally provide collaborative support to JAXA's Akatsuki mission.

A novel cloud tracking method and results from Akatsuki

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In this prestation, we present a novel automated cloud-tracking method and its error evaluation used to process data from Akatsuki. Also, we present rich examples of cloud tracking and the subtlety.

Our method is based on the traditional template match, but we use multiple images harmoniously to derive consolidated cloud motion vectors. This method improves the precision and decreases the erroneous template match. The resultant first guess is improved by a relaxation-labelling approach. For this purpose, we have developed an evaluation based on the principle that we termed as “deformation consistency.” Accuracy evaluation is particularly important for quality control. We have devised the precision measurement based on the sharpness of cross-correlation surface peaks. We further conduct screening based on deformation consistency.

In this presentation, we will provide examples of cloud tracking results and how they are compared with radiance images. We will also present topics of interest from case studies. Of particular interest would be atmospheric disturbances at lower-to-middle cloud layers and at the cloud top, as well as the vertical structure of winds and multi-altitude signals from the two-wavelength observation at 283 and 365 nm.

Part of the topics of this presentation has been published in the following papers:

Ikegawa and Horinouchi (2016) *Icarus,* 271, 98-119, doi:10.1016/j.icarus.2016.01.018.

Horinouchi et al. (2017) *Measurement Science and Technology,* 28(8), 085301, doi: 10.1088/1361-6501/aa695c.

Horinouchi et al. (2018) *Earth, Planets, Space*, 70:10, doi:10.1186/s40623-017-0775-3.

WINDS IN THE MIDDLE CLOUD DECK FROM 965 AND 1010 NM IMAGING BY THE VMC ONBOARD VENUS EXPRESS

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For more than eight years the Venus Monitoring Camera (VMC) [1] onboard the Venus Express orbiter performed continuous imaging of the Venus cloud layer in UV, visible and near-IR filters. We applied the correlation approach to sequences of the near-IR images at 965 and 1010 nm to track cloud features and determine the wind field in the middle and lower cloud (49-57 km). From the VMC images that spanned from December of 2006 through August of 2013 we derived zonal and meridional components of the wind field [2]. Zonal and meridional profiles are presented at Fig.1. Zonal speed obtained in 965 nm channel is very close to value obtained in 1010 nm. In low-to-middle latitudes (5-65ºS) the velocity of the retrograde zonal wind was found to be 68-70 m/s. Meridional speed profiles are different in equatorial region. Whereas the meridional wind speed in 965 nm slowly decreases from peak value of +6.5 m/s at 15ºS to 0 at 65-70ºS, in the 1010 nm this component demonstrates 0 values near the Equator, then slowly increases to peak value about +3.5 m/s at 25ºS and again slowly decreases to 0 at 65-70ºS. The mean meridional speed has a positive sign at 5-65ºS suggesting equatorward flow in both channels. This result, together with the earlier measurements of the poleward flow at the cloud tops [3] indicate the presence of a closed Hadley cell in the altitude range 55-70km. Long term variations of zonal and meridional velocity components were found during 1200 earth days of observation. In 965 nm channel at 20º±5ºS the zonal wind speed (by absolute value) increases from -67.2 m/s to -77.3 m/s. The meridional wind gradually increases from +1.3 m/s to +8.5 m/s [2]. Aphrodite Terra, Atla Regio and Phoebe Regio have a significant influence on the circulation in the middle cloud deck. As in the case of the cloud top winds [4] maps of mean zonal and meridional components derived from the VMC imaging demonstrate an influence of the Venus topography on the velocity of the horizontal flow in both near-IR channels. Following Bertaux et al. [4] we explain this effect by influence of stationary gravity waves.

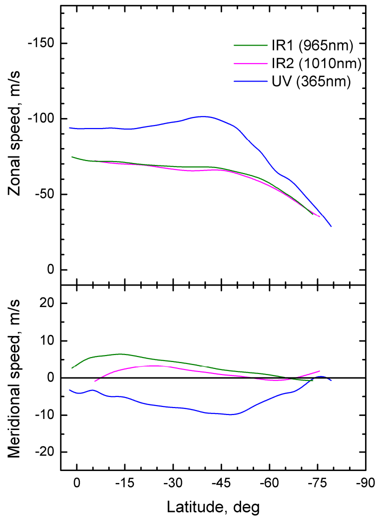

Fig.1 Mean zonal (top) and meridional (bottom) wind latitudinal profiles, UV (blue, [3]), IR 965 nm (green, this work) and IR 1010 nm (magenta, this work).

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An improved cloud tracking method applied to Akatsuki UVI images to study atmospheric circulation in the Venusian polar region

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The atmospheric circulation and the associated material transport in the Venusian polar region are thought to be crucial for the maintenance of the global cloud/atmospheric structure. In the ultraviolet range, Venusian cloud shows various patterns created by the transport of "unknown" UV absorber, which can provide information both on dynamics and chemistry in this region. Wind velocities have been measured by cloud tracking using images obtained sequentially in such ultraviolet range. In the previous cloud tracking studies, equirectangular projection images have mostly been used; however, cloud patterns in the high latitude tend to be stretched in the east-west direction in equirectangular projection, making identification of small-scale features suitable for cloud tracking difficult. In this study, we apply cloud tracking to the polar region in polar projection by using the "rotation invariant phase only correlation method" considering the rotation of the cloud patterns. The derived velocity field is compared with the cloud morphology to understand the role of dynamics in shaping the clouds. The data used are 365 nm images taken by UVI onboard JAXA' Akatsuki. We also derive rotational components from the rotation angle of the image and examine the difference between rotational component obtained from the wind field and obtained from the rotation angle of the image. Initial results show sporadic occurrence of high-latitude jets that are faster than the average wind speed derived from the ultraviolet images taken by VIRTIS by Hueso et al. (2015) in the latitude of 50-70 degrees.

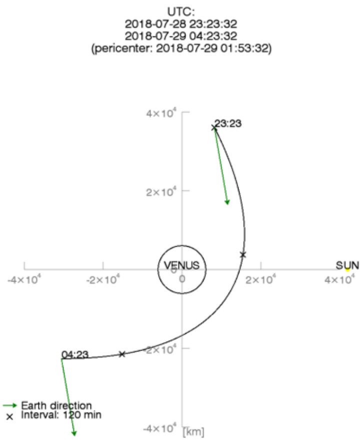
Simultaneous Wind Measurements with Thermal and Microphysical Properties Investigations at Cloud Tops during Akatsuki's July 29, 2018 Pericenter Passage : a Joint CFHT – Akatsuki Campaign

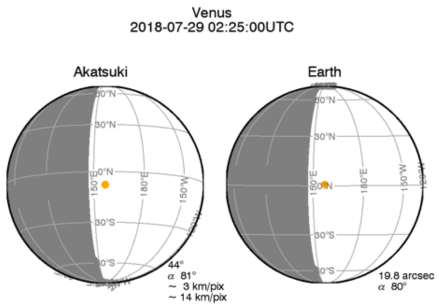
Thomas Widemann, Pedro Machado, Yeon Joo Lee, Takeshi Imamura, Claire Moutou, Ruben Gonçalves

We report on a joint observing program of July 28-29, 2018. The 3.60-meter Canada-France-Hawaii telescope (CFHT) with ESPaDOnS visible spectrograph provides high-resolution spectra (R~80000) from 0.37 to 1.05 μm. It will map cloud top winds at the same time and with the same geometry as UVI and LIR observations during Akatsuki's pericenter observations of July 29 02:25 UTC (July 28 16:25 HST).

ESPaDOnS and the sequential technique of visible Doppler velocimetry has proven a reference technique to measure instantaneous atmospheric circulation. Perihelion observing from Akatsuki allows for UVI cloud morphology ans microphysical properties of aerosols at cloud top level. This will also be compared to Akatsuki LIR imaging near 10 μm that will observe cloud-top temperature in the same region.

Doppler winds from Earth are the only way of simultaneous wind, thermal & microphysical investigations near Akatsuki's pericenter. Preliminary results will be presented at the meeting.





TRACES OF SURFACE TOPOGRAPHY IN VENUS ATMOSPHERE FROM THERMAL INFRARED SPECTROMETRY

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We study the traces of influence of the Venus' topographic features on the Venus atmosphere. From Fourier Spectrometry on Venera-15 (FS V-15), the 3-D temperature and clouds fields in mesosphere were obtained (temperature and aerosol profiles were retrieved in self consistent way from each single spectrum [1]). Geometry (orbits trough North pole) and spectral range (40-1650 cm-1) allow to study Venus atmosphere in the Northern hemisphere on the day and night sides practically simultaneously (within 1 - 2 h) through 12 h local time from N-pole to 20N and altitudes from 55- 60 km to 90-100 km. Earlier it was found that distribution of temperature at different levels vs. local time is described by the Fourier decomposition with 1, 1/2, 1/3, and 1/4 and upper boundary of clouds with 1, 1/2 days harmonics in Solar-fixed coordinates. The amplitudes of diurnal and semi-diurnal harmonics reach 10 K. We found that in the Solar- fixed coordinates both maxima and minima are shifted from noon and from midnight to westwards by of 2 - 3h [1]. To study how the surface influences on the atmosphere we compare the isotherms at different levels in the mesosphere and position of the upper boundaries of clouds with Magellan topography maps [2]. Of course, in retrieval of temperature and aerosol procedure we don't use any information about surface topography. For low boundary condition we take the temperature and pressure at 50 km altitude from VIRA: it is 5 points for latitudes <30°, 45°, 60°,70° and 85°. Isotherms and clouds isolines repeat the most pronounced details of relief but the "images" shifted by~30° (of 2 hours) in the direction of superrotation relative to topography map. Thus "image" of relief in the atmosphere and extrema of thermal tides are strongly linked.

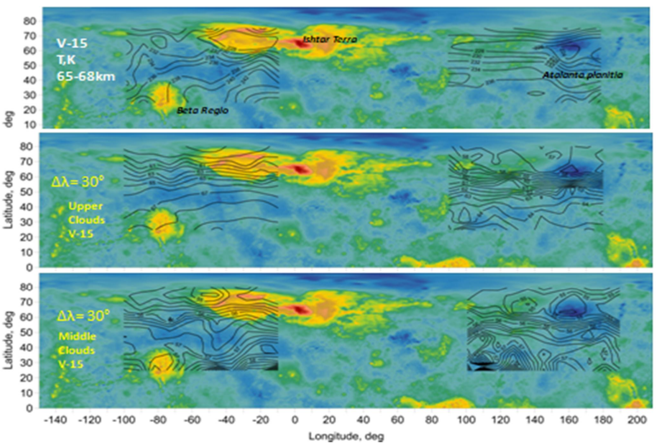

Fig.1 Examples of isotherms (V-15, Northern hemisphere) at upper boundary of clouds (upper), altitude of position of upper boundary of clouds (altitude of opacity equal to 1 in thermal IR) (middle) and middle clouds (bottom) plotted above the Magellan topography map. One may see that the isotherms and the isolines of the clouds boundary altitudes reproduce the most pronounced surface features Ishtar, Atalanta Planitia and Beta Regio. Temperature at the upper boundary of clouds decreases along with the increase of surface altitude. Correlation with the surface details reaches 80-90 %.

It was found by [3] that surface topography influence the wind speed in UV (VMC VEX) above Aphrodite Terra trough stationary gravity waves, generated in the lower atmosphere. Problem is how gravity wave overcome nonstable region in the middle clouds? After more detailed study UV VMC data [4] absolute minimum of wind speed above Aphrodite Terra was identified exactly at noon. It looks like atmosphere becomes more stable, may be as a result of Solar heating. For thermal IR it is known even from ground based observations of 1960th (also OR Pioneer Venus, FS V-15 etc.) that extrema of thermal tides are shifted from noon and midnight (by 2-3 hours), which was explained by input from superrotation. As well a bow shaped feature , observed by Akatsuki above Aphrodite Terra is found also at 2 - 4 h afternoon [5]. For observation in UV the altitudes of 70 -72 km are available. The difference in altitude of effective levels between thermal IR (65-68 km) and UV may exceed 5 km. Different local time behavior relative to noon between UV and IR may be explained by changing the phase with depth in the clouds. We found strong link between solar tides and extreme surface topography which may indicate as in the case of Mars, that we deal with non-migrating solar tides.

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Vertical propagation of the large stationary gravity waves in the Venus atmosphere

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The Longwave Infrared Camera onboard Akatsuki has observed a large bow-shaped stationary temperature feature [Fukuhara et al., 2017]. It extended from the northern polar region to the southern polar region across the equator, and stayed near the evening terminator for four earth days at least in contrast to the background wind speed of about 100 m s^-1 at the cloud-top level. Furthermore, Kouyama et al. [2017] has reported that the stationary features repeatedly appeared only above the highlands in the low latitudes in the afternoon. A simple numerical simulation using a model based on Imamura [2006] suggested that the stationary feature is caused by a gravity wave propagating from near the surface [Fukuhara et al., 2017]. However, conditions under which the wave can propagate are still unknown. In the present study we investigated the wave propagation in the numerical simulation under various conditions of the static stability and eddy diffusion coefficient in the cloud layer in the altitude range of 45–55 km.

For all simulation cases with several different thicknesses of a near-neutral layer around the cloud-top level, the waves with a vertical wavelength of around 30 km can propagate from near the surface to the cloud-top level, though the amplitude of the wave at the cloud-top level changes for a factor of two. For cases with an eddy diffusion coefficient much larger than the nominal value, the stationary waves are also hardly damped. It is found that the Venus atmosphere is transparent to the gravity wave with a long vertical wavelength. These results suggest that the occurrence of the stationary gravity waves with a long vertical wavelength depends not on the conditions under which the waves pass through the atmosphere but rather on the presence or absence of the wave excitation source near the surface. The local time and surface topography dependence of the wave excitation implies that the source might be a mountain wave generated by solar heating. The process and condition of the wave excitation should be investigated using numerical simulation in consideration of the surface topography and radiative process in the lower atmosphere.

Polarimetric observation of ice crystals in Venus cloud with Pirka telescope

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Venus is entirely covered by cloud which is mainly composed of concentrated solutions of sulfuric acid and locate at the altitude of 45-70 km. There is a little H_2O also and it has been pointed out that the possibility of the existence of ice crystals from the fact that the cloud top temperature is under the freezing point.

It is known that the degree of polarization shows some significant differences between ice crystal and droplet. The degree of polarization of ice crystal decreases by 0.3 % at the scattering angle of 22 degrees and we call it as 22-degree halo. L'Oreary (1972) carried out polarimetric observation at the wavelength of 550 and 650 nm, but they did not find the feature of 22-degree halo. Können et al. (1993) conducted the same observation at 8 wavelengths between 402 and 850 nm. Their results sometimes showed the indication of degree of the signature of ice crystal, however, it is not always the case.

We started the polarimetric observation with MSI (Multi-Spectral Imager) mounted on the 1.6-m Pirka telescope operated by Hokkaido University to investigate the existence of ice crystals. Since the distribution of cloud top temperatures is important to ditermine whether water can freeze, we focused on the spatially resolved polarimetric observation to capture the large scale UV albedo pattern at the cloud top altitude.

In this presentation, we will report the results of observation on Apr.-May, June-July 2018 and introduce observation plan in Sept.-Oct. 2018.

The large variability of H_2O and SO_2 in the atmosphere of Venus above the cloud tops is puzzling, especially since there is little evidence for their variability in the lower atmosphere. We note three important related facts: (1) The abundances of H_2O and SO_2 in the deep atmosphere are of the same order of magnitude ~10-40 ppm, (2) there is a rapid decrease in H_2O and SO_2 just above the cloud tops, resulting in sharp vertical gradients in their vertical profiles, and (3) the primary removal mechanism for H_2O and SO_2 above the cloud tops is formation of H_2SO_4 aerosols. In this talk we examine the possibilities that H_2O and SO_2 could be regulated in a chemistry-transport model and related consequences for microphysical cloud modeling.

Above the cloud tops, SO_2 exchanges rapidly with SO and SO_3. However, formation of H_2SO_4 followed by condensation sequesters SO_2 in aerosol particles and remove it from active chemistry. The reaction that forms H_2SO_4 appears to involve a complex with H_2O:

$$SO_3 + H_2O = SO_3 \cdot H_2O \qquad SO_3 \cdot H_2O + H_2O = H_2SO_4 + H_2O$$

Using the CARMA 3.0 microphysical cloud model with model atmospheres from the Caltech/JPL KINETICS photochemical model we can describe changes in the Venus atmosphere due to variations aerosol distribution from the equator to the poles, effects due to changing lower boundary conditions, and effects due to changes in chemistry due to water nominal, water rich, and water poor conditions, specifically:

Photochemical Modeling:
1. SO_2 and H_2O can regulate each other via formation of H_2SO_4
2. Small changes in the transport rates for SO_2 may result in large changes in SO_2 above the cloud tops.
3. Below a critical value, H_2O could be completely sequestered by H_2SO_4 aerosols (chemical bifurcation).
4. The combination of the above could explain some of the observed variabilities in SO_2 and H_2O on Venus.

Microphysical Cloud Modeling using photochemical model atmospheres:
1. Using model atmospheres with different lower boundary water mixing ratio values for water definitely affects the microphysics equatorial latitudes and exhibits particularly extreme behaviour different for chemical bifurcation cases corresponding to a collapsed water condition in the atmosphere.
2. This difference is more than PVO vs. VEx epoch differences.
3. Large differences occur in the precipitation cycle at the equator (a factor of ~3 decrease in timescale from 15 ppm to 35 ppm lower boundary water mixing ratio values (i.e. ~2 years vs ~8 months).
4. Upper haze layer (84 km) at all latitudes shows a large increase in 0.3-0.6 micron sized particle when comparing a 15 ppm lower boundary water mixing ratio to 35 ppm, particularly at the poles.
5. This makes sense, since with a chemical bifurcation there is much more SO_2 present under collapsed water conditions.

Title

Interaction between the thermosphere and the cloud-level atmosphere of Venus studied with simultaneous observations by Hisaki and Akatsuki

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Abstract

Observations of the Venus' upper atmosphere using the Extreme Ultraviolet Spectroscope for Exospheric Dynamics (EXCEED) on the space telescope Hisaki revealed an existence of periodical variations in airglow intensities on the dawn side, suggesting that atmospheric waves propagate from below atmosphere up to the thermosphere to cause oxygen density variation (e.g., Masunaga et al., 2017). To confirm such vertical coupling via propagating waves, simultaneous observations of the cloud-level atmosphere (~50 – 70 km altitude) and the thermosphere are required.

Spacecraft Akatsuki is orbiting Venus since December 2015, and is observing cloud-level atmosphere of Venus with four imagers. Hisaki and Akatsuki observed Venus upper and middle atmospheres simultaneously in June 2017. We analyzed time series of the EUV OI (130.4 nm and 135.6 nm) dayglow intensity measured by EXCEED and the UV brightness (365 nm) obtained by the Ultraviolet Imager (UVI) on Akatsuki. The OI emission implies the column density of oxygen atoms and/or photoelectrons in the thermosphere, and the UV reflectivity is affected by the amount of unidentified absorbers at the cloud top.

In both data, we identified the same periodicity of 3.5 days. This periodicity seems to be associated with Kelvin waves at the cloud top, according to our cloud tracked winds from UV images; however, Kelvin waves should decay with height through radiative damping and will not reach the thermosphere. We propose an indirect process in which the Kelvin waves change the wind field periodically and this oscillating wind influences the vertical propagation of small-scale gravity waves.

Title:

Coordinated observations using the ground-based IR heterodyne spectrometer and Akatsuki/RS in 2018

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The most extensive observations of Venusian middle and upper atmosphere (80-160 km altitude) have been performed by Venus Express (VEX) up to 2014 (e.g., Pätzold et al., 2007; Mahieux et al., 2015). These observations have found the highly spatial and temporal variation in the thermal structure in the region. The discrepancies of the temperature between 80 km and 100 km have not been properly interpreted by GCM numerical studies (Bougher et al., 2015; Gilli et al., 2017). One of the proposed causes is the wind shear of transition from super-rotation to subsolar-to-antisolar flow. However, the global dynamics in the mesosphere and the lower thermosphere have not been well understood due to lack of observations.

We will perform comprehensive observations of temperature and wind variations in Venusian mesosphere and lower thermosphere in June 2018 using Mid-Infrared Laser Heterodyne Instrument (MILAHI) attached to our dedicated Tohoku University 60 cm reflective telescope at Mt. Haleakala, Hawaii (Nakagawa et al., 2016). One of the purposes of this MILAHI observations is to make coordinated observations with Radio Science (RS) experiments onboard Akatsuki. Akatsuki/RS measures the temperature profile from 45 km to 90 km altitude. We can compare its profile with the temperature profile obtained by MILAHI. The coordinated observations are help to understand the interaction of temperature and wind.

Eight years of VEX-VeRa radio sounding of the Venus atmosphere

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The Venus Express Radio Science Experiment VeRa performed regular radio-sounding experiments of the Venus neutral atmosphere using the spacecraft radio subsystem in the one-way radio mode at X-band (8.4 GHz) and S-band (2.3 GHz). The radio links were stabilised by a dedicated onboard ultrastable oscillator. More than 800 atmospheric profiles could be retrieved between July 2006 and January 2014. Radial profiles of neutral number density from the atmospheric-induced Doppler shift during the occultations cover the altitude range from the upper troposphere (~40km) to the upper mesosphere (~90 km). These are then used to derive vertical profiles of temperature and pressure. The spatial coverage of previous radio occultation measurements is generally quite limited, but the extensive VeRa data set covers almost all latitudes, longitudes, and local times, thus providing the unique opportunity to study the global atmospheric structure and dynamics at high vertical resolution. Static stability profiles retrieved from the data provide valuable information about atmospheric instabilities in the region of the middle cloud layer. Small-scale fluctuations in the thermal profiles reveal significantly enhanced gravity wave activity in the adjacent lower mesosphere with a strong latitudinal gradient. Global-scale wave phenomena can also be retrieved from the data set. Thermal tides are especially pronounced at low latitudes with a dominating semidiurnal wave structure in the upper mesosphere. The tides are generated in the cloud layer and propagate upwards and downwards from this region, leading to a redistribution of momentum and energy in the Venus atmosphere. The thermal profiles can also be used to retrieve zonal winds if the assumption of cyclostrophic balance is applied. The presentation will give a comprehensive overview of the atmospheric scientific results that could be achieved with VeRa so far.

Eight years of VEX-VeRa radio sounding of the Venus ionosphere

M. Pätzold (1), B. Häusler (2), S. Tellmann (1), M.K. Bird (1,3), D.P. Hinson (4), G.L. Tyler (4), J. Oschlisniok (1), K. Peter (1), T. Imamura (5), H. Ando(6), T.P. Andert (2), S. Remus (7)
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The Venus Express Radio Science Experiment VeRa sounded the Venus ionosphere from 2006 to 2013 at two coherent downlink frequencies driven by an Ultrastable Oscillator (USO). The use of the dual-frequency one-way radio link at X-band and S-band allows the derivation of the true ionospheric electron density profile without contributions or perturbations by the spacecraft´s residual or periodic vibrational motion. More than 900 electron density profiles from 15 occultation seasons in eight years of operation from solar minimum 2007 to solar maximum 2014 were recorded. The observations cover almost all solar zenith angles, local times and planetary latitudes. On average, the Venus ionosphere shows a large-scale two-layer structure with a well defined base at 110 km altitude, a lower layer V1 formed by photo-ionisation of solar X-ray and secondary ionisation and a main layer V2 formed by solar EUV. Peak densities and altitudes of both layers depend on the influx of solar radiation and the solar zenith angle. The transport region between the topside and the ionopause shows a variety of plasma scale heights. The ionopause is identified in most cases and their varying altitude depends on the pressure balance between the solar wind and the ionospheric plasma. The V2 peak density as a function of solar zenith angle follows the well known Chapman relation but the V2 peak altitude is constant at 140.7 km for solar zenith angles <65° but shows an increasing scatter for larger solar zenith angles but does not drop to lower altitudes in contrast to PVO observations (Cravens et al., 1981). A sporadic layer of extra ionisation below V1 is still under investigation and may be caused by enhanced ionisation of NO2 as Peter (2018) has concluded from Mars Express radio sounding of the Mars ionosphere.

Ion temperature anisotropies in the Venus plasma environment at solar minimum

Alexander Bader, Gabriella Stenberg Wieser, Mats André, Martin Wieser, Yoshifumi Futaana, Hans Nilsson, Moa Persson

Velocity distributions are a key to understanding the interplay between particles and waves in a plasma. Any deviation from a Maxwellian distribution may be unstable and result in wave generation. We use data from the ion mass spectrometer IMA (Ion Mass Analyzer) and the magnetometer MAG onboard Venus Express to study ion distributions in the plasma environment of Venus.

We focus on the temperature anisotropy, that is, the difference between the ion temperature perpendicular and parallel to the background magnetic field. We present spatial maps of the average ratio between the perpendicular temperature and parallel temperature, both for proton and heavy ions (atomic oxygen, molecular oxygen and carbon dioxide).

Furthermore we calculate average values of the perpendicular and parallel temperature for different spatial areas around Venus. Our results show that the perpendicular and parallel temperatures for protons are nearly equal in the solar wind. At the bow shock and in the magnetosheath, the ratio between the perpendicular and parallel temperature increases to provide conditions favouring mirror mode wave generation, which agrees with such waves being observed there.

Solar wind interaction with Venus: From the planetary interior to interplanetary space

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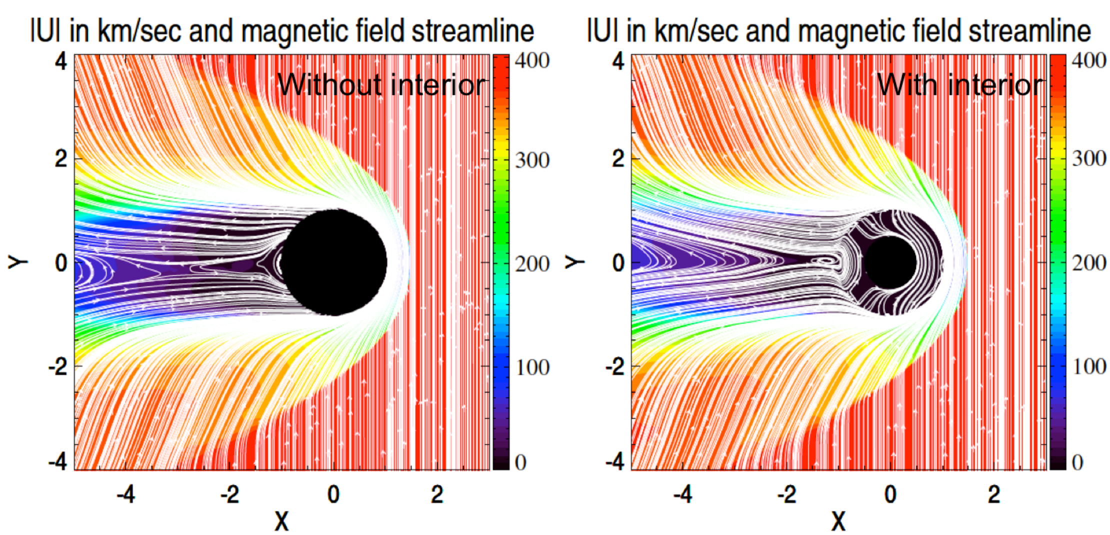
Unmagnetized planets, like Venus, are especially susceptible to atmospheric scavenging because the solar wind interacts directly with the upper atmosphere due to the lack of an intrinsic dipole magnetic field. Recent Venus Express (VEX) observations confirmed the complexity of the induced Venusian magnetosphere, especially given the observed magnetic reconnection in the near Venusian magnetotail. On the other hand, penetration of the interplanetary magnetic field (IMF) into an insulating crust is routinely seen at the moon but the ionosphere of Venus presents an induced field barrier whose ability to shield the body varies with external plasma and field conditions. We expect Venus to be influenced by penetrating IMF in certain circumstances, and explore the observational and physical consequences. We study the solar wind interaction with Venus, for the first time, by incorporating the planetary interior in a fully self-consistent manner. We mainly focus on the influence of the coupled planetary interior (such as the conducting core size and the electrical conductivity profiles) on 1) the atmospheric ion loss of Venus and 2) the Venusian magnetic topologies under selected solar wind conditions. With the knowledge from 2) combined with VEX observations, this work will enable further constraining and help determine the Venusian interior structures and properties. This new model is capable of revealing how external IMF propagates from interplanetary space to satellite altitudes and all the way down to the surface and planetary interior in a self-consistent way, and thus allow us to investigate the transition to more moon-like plasma interactions.



MPVIEW : A multi-satellite mapping system to fully monitor and characterize waves in Venus' atmosphere

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MPVIEW(Multi Platform Venus Imager to Elucidate Waves) is a small multi-satellite mapping system to fully monitor and characterize waves in Venus' atmosphere. It is deployed sequentially by a mother spacecraft initially inserted in a high apoapsis equatorial orbit during the downsizing of the initial orbit to the final orbit of observation.

To understand the angular momentum budget that maintain superrotation, general circulation models are valuable tools. They show that mean meridional circulation, thermal tides (diurnal and semi-diurnal components) and planetary-scale waves (periods around 4-6 Earth days, wavenumbers 1 or 2) play a role in this subtle balance. To validate the simulations, it is crucial to characterize these three components through observations. However, these observations and characterizations are difficult. One way would be to monitor the full range of longitudes during a significant time period. Thermal infrared is the only wavelength range where day and night sides can be observed at the same time.

Such a coverage would give the temperature, zonal and meridional wind fields at the cloud-top, and could help characterize the major players in the angular momentum transport, at least near the cloud-top. While it is not enough to fully characterize the circulation through observations only, it would be a crucial constraint to validate circulation models.

This coverage would also give access to a full monitoring of the stationary waves that have been observed by Akatsuki and that are related to interaction of mountains with the near-surface flow. This monitoring (timing, frequency, position, variability of the bow-shaped waves) would give constraints on the modeling of the near-surface circulation, which is an additional and very valuable constraint on the GCM simulations and on the atmosphere-surface interaction.

The ideal configuration to monitor waves would be a constellation of 3 small satellites all orbiting Venus on the same equatorial circular orbit and located at 120° from each other, that is forming an equilateral triangle. These satellites have to be equipped with a long wave infrared camera similar to the LIR instrument onboard Akatsuki providing a full thermal infrared image of a wide equator-centered latitudinal band. Assuming a typical field of view of 0.3 rad and a scale of 1 mrad/px, and a typical orbit radius of 40 000 km, each imager would cover the whole Venus disk with a nadir spatial resolution of ≈40 km.

The most natural way to proceed is to release 2 small nadir-pointing satellites from 1 mother spacecraft after Venus equatorial orbit insertion and to use the mother spacecraft as a third observation platform. It is not possible to achieve the ideal configuration described above, which would require unrealistically large propulsion resources. Assuming that the main spacecraft in inserted in a large apoapsis elliptical orbit with a further progressive reduction of the apoapsis altitude, it is relatively easy and only little energy-consuming to release the small satellites from predefined intermediate orbits. In this way, the 3 observation platforms may be placed on coplanar elliptical orbits of different apoapsis (and to some extent periapsis) altitudes, with different orbital periods, allowing to observe simultaneously several longitude ranges.

We will present the results of a preliminary study aiming at characterizing the best solutions in terms of orbit parameters and periods to maximize the longitudinal coverage of MPVIEW in order to monitor and fully characterize the complex wave system in Venus' atmosphere.

THIRTY DAYS ON VENUS: CHEMICAL AND ELECTRICAL CHANGES MINERALS EXPOSED TO THE GLENN EXTREME ENVIRONMENT RIG (GEER). M. S. Gilmore[1], A. R. Santos[2], J. P. Greenwood[1], N. Izenberg[3], G. Hunter[2], A. Treiman[4], and D. Makel[5], [1]Wesleyan University, 265 Church St., Middletown CT, 06459 USA mgilmore@wesleyan.edu, [2]NASA Glenn Research Center, Cleveland OH, [3]Applied Physics Lab, Laurel, MD, [4]Lunar and Planetary Institute, Houston TX. [5]Makel Engineering, Chico, CA.

The NASA Glenn Extreme Environment Rig (GEER) is a pressure vessel that can simulate Venus conditions of pressure, temperature and atmospheric composition. We placed a number of natural mineral samples in GEER at an approximation to Venus conditions: T = 733 K, P = 93 bars, 96.5% CO_2, 3.5% N_2, 180 ppm SO_2, 51 ppm OCS, 30 ppm H_2O, 12 ppm CO, 2 ppm H_2S, 0.5 ppm HCl and 2.5 ppb HF. The run lasted 30 days at Venus conditions. Minerals were selected to address two sets of questions:

Venus Apatites. Several of the mountaintops of Venus display anomalous radar emissivity and backscatter that has been explained as a consequence of the presence of ferroelectric minerals at high elevations, where ferroelectric minerals are created or precipitated in rocks over time by chemical reaction(s) with the ambient atmosphere [1,2]. That basaltic rocks and tessera materials both show this change in radar emissivity and backscatter suggests a ferroelectric mineral that is ubiquitous in igneous rocks [3]. We seek to test the hypothesis of [2] that exposed grains of fluorapatite ($Ca_5(PO_4)_3F$), the more common apatite mineral in igneous rocks on Earth [2-4], will convert to chlorapatite ($Ca_5(PO_4)_3Cl$), which is ferroelectric, under Venus surface conditions. To test this idea, in this experiment we reacted two fluorapatites and one chlorapatite.

Venus Surface Mineralogy In-Situ Instrument System (V-Lab). V-Lab is a proposed *in situ* reaction chemistry experiment where geological materials whose core properties may change over time upon exposure to the Venus atmosphere will be placed on a microsensor platform. Changes in this geological material as monitored through electrical measurements will give an indication redox solid-gas reaction(s) in the Venus environment. Comparison of the reaction chemistry between different material types will provide an improved understanding of the effect of the Venus surface atmosphere on known geological materials. In our experiment, we sought to determine if any compositional and/or electrical properties changed in samples upon exposure to simulated Venus atmosphere in GEER over a 30-day run. The results will help us to focus on minerals that are good candidates for a platform like V-Lab. The reactants include: hematite (α-Fe_2O_3), magnetite (Fe_3O_4), anhydrite ($CaSO_4$), pyrite (FeS_2), a mid-ocean ridge tholeiitic basalt (Juan de Fuca) and calcite ($CaCO_3$).

Analyses. Color changes are observed in some apatite samples after the GEER run. The minerals will be analyzed by with a Hitachi Field Emission Gun Scanning Electron Microscope SU 5000 (FE-SEM). Elemental maps with sub-micron scale resolution will be produced and examined to document the alteration products of the minerals. For the apatites, we will look to see whether ferroelectric phases such as chlorapatite are formed due to reaction in a Venus-like atmosphere over the time frame of the experiment. For all solid samples, we will look for compositional changes due to solid-gas reactions.

We will also test if the reactions in the Venus chamber produce changes in electric properties of tested solids. The electrical impedance and capacitance of several samples (two of the apatites, hematite and magnetite), measured both before and after the GEER run, will be analyzed and compared. Such changes may be relevant to the anomalous radar behavior at high altitudes on Venus.

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VERITAS (VENUS EMISSIVITY, RADIO SCIENCE, INSAR, TOPOGRAPHY AND SPECTROSCOPY): A PROPOSED DISCOVERY MISSION.

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Introduction: VERITAS addresses one of the most fundamental questions in rocky planetary evolution: why did these twin planets diverged down different evolutionary paths? Venus may hold lessons for past and future Earth. Venus' hot lithosphere may be a good analog for early Earth, which may limit the development of plate tectonic [1]. Determining the factors that lead to the initiation of plate tectonics would inform our predictions for rocky Earth-sized exoplanets. The conditions leading to Venus' greenhouse atmosphere may also inform our understanding of Earth's future. VERITAS would answer key questions about Venus' geologic evolution, determine what processes are currently active, and search for evidence for past or present water.

Payload: The VISAR X-band [2] measurements include: 1) a global digital elevation model (DEM) with 250 m postings, 5 m height accuracy, 2) Synthetic aperture radar (SAR) imaging at 30 m horizontal resolution globally, 3) SAR imaging at 15 m resolution for targeted areas, and 4) surface deformation from RPI at 2 mm precision for targeted, potentially active areas.

VEM [3] will produce surface coverage of most of the surface in six NIR bands located within five atmospheric windows and of eight atmospheric bands for calibration and water vapor measurements.

VERITAS will use Ka-band uplink and downlink to create a global gravity field with 3 mgal accuracy at 145 km resolution (130 spherical harmonic degree and order or d&o) and providing a significantly higher resolution field with much more uniform resolution than that available from Magellan.

Geologic Evolution: VERITAS answers key science questions via: 1) examining the origin of tesserae plateaus -possible continent-like features, 2) assessing the history of volcanism and how it has shaped Venus' young surface, 3) looking for evidence of prior features buried by volcanism, and 4) determining the links between interior convection and surface geology. In particular, VERITAS will examine the stratigraphy and nature of tesserae deformation features, determine the processes modifying impact craters, search for evidence of pre-existing features such as buried impact basins, and determine the origin of tectonic features such as huge arcuate troughs that have been compared to Earth's subduction zones.

Water and Surface Composition: VERITAS looks for the chemical fingerprint of past water in the form of low Fe, high Si rock in the tessera plateaus and larger tesserae inliers [4], and for present day volcanic outgassing of volatiles in the form of near surface water variability associated with recent or active volcanism.

Current Activity: Several studies have found evidence of current or recent volcanism on Venus. [e.g., 10]. VERITAS uses a variety of approaches to search for present day activity, including 1) tectonic and cm-scale volcanic surface deformation, 2) chemical weathering, 3) thermal emission from recent or active volcanism, 4) topographic or surface roughness changes, and 5) comparisons to past mission data sets.

Gravity: The Magellan spherical harmonic gravity field has an average resolution of only 550 km [7], which is too low to determine elastic thickness [8]. VERITAS data, with an average resolution of 145 km, will enable estimation of elastic thickness (a proxy for thermal gradient) and resolution of specific geologic processes [9].

Conclusions: VERITAS will create a rich data set of high-resolution topography, imaging, spectroscopy, and gravity. These co-registered data will be on par with those acquired for Mercury, Mars and the Moon that have revolutionized our understanding of these bodies. VERITAS would be an extremely high value asset for Venus exploration, providing very accurate topography and a surface composition map to optimize targeting of probe or lander missions as well as for later investigations of surface change.

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Remote Sensing Studies on Venus

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Venus, often regarded as Earth's twin planet that went astray has had a long history of exploration. However, major scientific questions regarding its composition, geology and structure remain quite unanswered. Though Venus is so like Earth in its size and mass, the existing conditions on this planet are quite ghastly. Venus is completely covered with clouds having high reflectivity, which makes the planet receive about 1.4 times lesser energy than Earth, despite being located closer to the Sun. Venus has not shown signs of plate tectonic activity but is definitely made up of a large number of volcanic structures.

Currently, the Venus Climate Orbiter, commonly referred to as *Akatsuki* is orbiting Venus with an attempt to study atmospheric stratification, atmospheric dynamics and cloud physics.

This paper shall present the conceptual design of a Venusian glider which shall glide into the atmosphere of Venus and thereby study its atmospheric parameters. With the help of this Venus glider, it is possible to study some regions of the surface as well. Remote sensing and IR studies from satellites orbiting the planet or ground station will help to a resolution of about 50km. The unique feature of the Venus glider is the in situ data collection and transmitting it back to the orbiter. The glider shall prelude a helical path into the atmosphere covering maximum range and providing good overview of the cloud profile. The location of study is based on the volcanic activity of the planet. This glider shall also be able to monitor the volcanic activity as long as it is airborne and able to send back data to the orbiter. Glider being small in size will reduces the cost and manufacturability. With the development of electronics which can survive at high temperature and harsh conditions, it shall play a crucial role in the study of Venus using the Venus glider. Multiple number of such gliders can be used to deploy at various places of the planet due it's compact size and stowed configuration.

The study of Venus is highly essential for us to understand despite physical similarities between Earth and Venus in terms of size, shape and mass, what caused it to be so different from that of Earth. This would help us gain insight into the birth and evolution and various surface processes that have occurred on our planet.

Session 08

Poster (2)

Prospects for an ancient dynamo and modern crustal remanent magnetism on Venus

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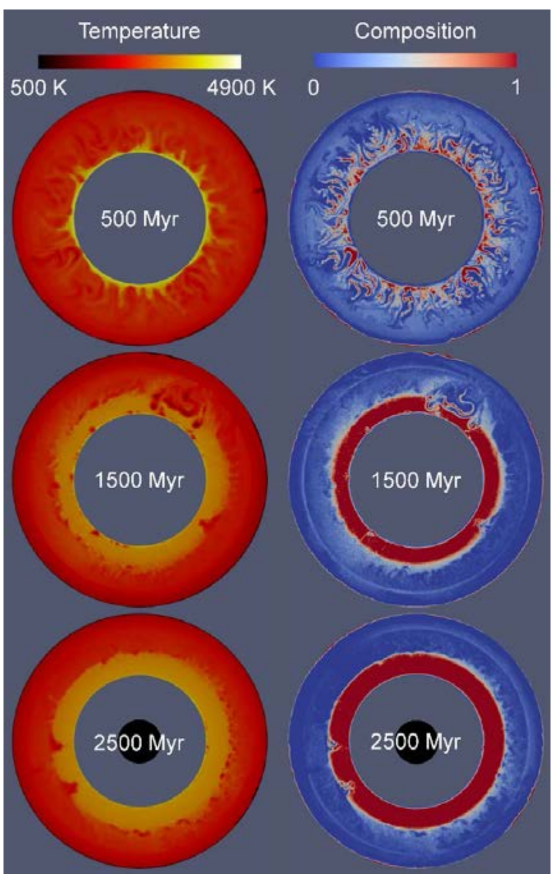
Venus lacks an internally generated magnetic field today. Whether one existed in the past is unknown, but critical to atmospheric evolution and potential habitability. Canonical models assume the core of Venus has Earth-like structure and composition, but is cooling too slowly for convection and thus a magnetic dynamo to occur today. Core/mantle heat flow is suppressed in these models after a putative transition in mantle dynamics associated with widespread, volcanic resurfacing. However, recent studies of impact craters and other surface features support more steady heat loss over geologic time. Precipitation of MgO and/or SiO_2 from the core can also drive compositional convection even with slow cooling. Here we reevaluate the likelihood that Venus has an "Earth-like" core using numerical simulations of the coupled atmosphere-surface-mantle-core evolution. A partially liquid, chemically homogenous core is only compatible with the modern lack of a dynamo if the thermal conductivity of core material is towards the higher end of modern estimates (i.e., >100 W/m/K). If lower estimates like ~40 to 50 W/m/K are actually correct, then we favor recent proposals of primordial, compositional stratification or complete solidification of the core. Any simulation initialized with a homogeneous, liquid core predicts a global magnetic field with Earth-like surface strength for >2 to 3 billion years after accretion—consistent with all available observations—and also sporadic activity within the surface age while temperatures remain below the Curie point of magnetite. Therefore, future spacecraft missions should perform the first-ever magnetometer measurements below the ionosphere to search for crustal remanent magnetism.



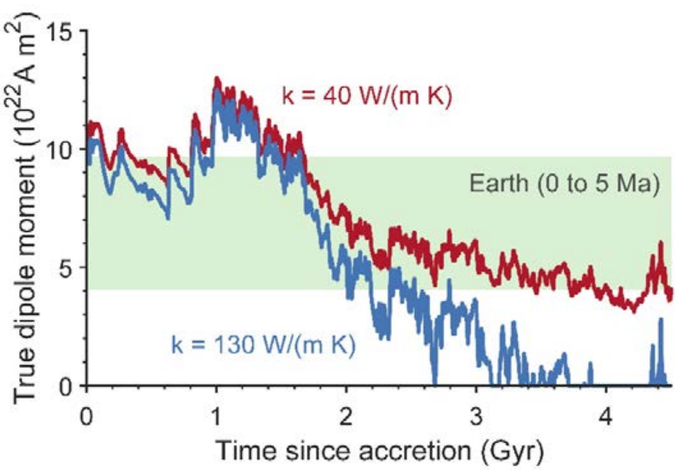


Figure 1 (above) | Predicted strength of the magnetic field over time for two values of thermal conductivity in the core. Green shading shows the recent variability of Earth's true dipole moment.

Figure 2 (left) | Representative snapshots of temperature and composition in the mantle. Composition ranges from 0 ("harzburgite") to 1 ("basalt"). The atmosphere and core are modeled with one-dimensional (vertical) parameterizations.

REINVISTIGATION OF VENUSIAN SPLOTCHES WITH MAGELLAN AND ARECIBO RADAR DATA. N. R. Izenberg[1] and J. A. Kelly[1,2]. [1]Johns Hopkins University Applied Physics Laboratory, Laurel, MD, USA (noam.izenberg@jhuapl.edu), [2]Liberty High School, Eldersburg, MD, USA.

Splotches, or airblast features are diffuse irregularly circular areas of radar contrast on the surface of Venus, likely caused by atmospheric pressure waves created by the disintegration and incineration of meteorites or comets too small to survive transit through the thick atmosphere the surface [1]. A total population of 401 was characterized by [2] using Magellan synthetic aperture radar (SAR) maps. Of the total, 138 splotches are also visible from earth via the Arecibo Observatory radar system [3]. The Arecibo data, although at lower spatial resolution (1 km/pixel at best, vs. 75 m/pixel at best of Magellan), was fully polarimetric, as opposed to the horizontal transmit-receive polarization of Magellan.

Splotch features are usually dark in SAR images, indicating a smooth, forward scattering, surface on the scale of 12-cm S-band radar [4]. This has been interpreted as shock waves and fine-grained ejecta like material, possibly the remains of the pulverized meteorite, covering the surface to some depth. Some splotches interact with topography such as ridges or rifts or tesserae, and some can have bright centers or concentric halos around the dark material (Fig. 1), possibly indicative of surface disruption or scouring effects [4].

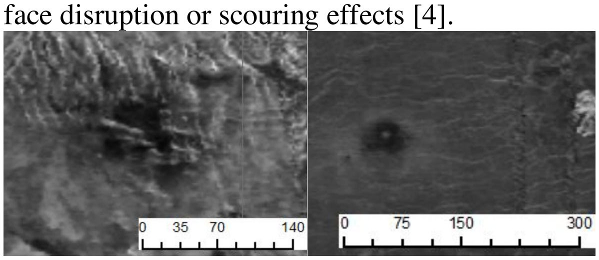


Fig. 1. Example splotches from Magellan global SAR images. Scales in km. Left: splotch #348 (-34.1, 359.5E) just south of Eve Corona. Right: Splotch #83 (36.1, 351.9E) in southeast Sedna Planitia.

In [5] we used profiling in SAR, direct comparison of Magellan and Arecibo radar backscatter, and Arecibo Same sense/opposite sense circular polarization (SC/OC) ratios to investigate the properties of a small pilot set of splotches in the Arecibo incidence angle vs. resolution 'sweet spot', and found examples where contrasts muted or reversed between the two data sets. Some differences are due to resolution, but in some cases, comparing Magellan/Arecibo backscatter of splotches Arecibo SC/OC ratios implied that the depths, compositions, or relationships of the splotch materials with the background varied.

We have begun a systematic evaluation of the splotches in the Magellan, Arecibo overlap, beginning with the ~59 in the Arecibo sweet spot region using both 2015 Arecibo data [6] and derived degree of linear polarization (DLP) and circular polarization ratio (CPR) data from Arecibo campaigns from 1999-2004 [3] and [7]. The derivation process results in the DLP and CPR maps having lower spatial resolution (12-16 km/pixel), which may be too coarse for small features like the center of Splotch #321 (Fig. 1) but is certainly sufficient for general comparison of large splotch features with surroundings. Early results show DLP values of some splotches indistinguishable from surrounding materials, and some with DLP slightly elevated from surroundings (Fig 2).

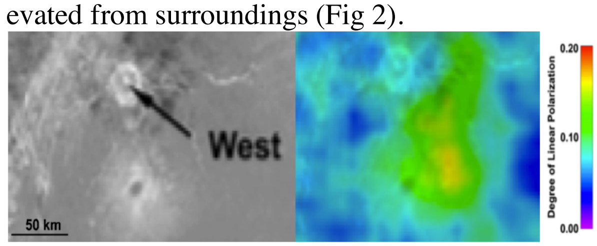


Fig. 2. Splotch #125 (25.1, 303.3E) south of crater West in Magellan SAR (left) and DLP (right) from [3]. The splotch DLP is elevated from the surroundings, though its relationship with West needs to be determined.

A deep (on the scale of several radar wavelengths) mantling of fine ejecta like material over more competent subsurface (e.g. lava flows) should show elevated DLP, so the lack of such a sign may be indicative of shallow deposits, or other material differences in some locations. We also are evaluating splotches in derived emissivity and roughness, and elevation data from Magellan altimetry and SAR stereo.

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Revisiting Crater Relaxation and its Implication on Venus. Saman Karimi, Department of Earth and Planetary Sciences. Johns Hopkins University, 301 Olin Hall, 3400 N. Charles St. Baltimore, MD, 21218 (saman@jhu.edu).

There is a strong connection between planetary geologic activities and internal heat transfer, and thus, investigating the geologic processes on the surface of a planet allows us to gain a better understanding regarding the planet's interior. Numerous studies of crater relaxation have been conducted on the surface of such planetary bodies as Mars, the Moon, and icy satellites in order to gain insight into the planetary structural and thermal history (e.g., *Karimi et al. 2016; Karimi and Dombard 2016, Karimi and Dombard 2017*). Unlike the surfaces of the Moon and Mars, the surface of Venus is not highly cratered. Therefore, unsurprisingly, few studies have explored relaxation of Venusian craters (e.g., *Grimm and Solomon 1988; Karimi and Dombard 2017*). Examinations of the limited Venusian craters demonstrate that they are generally shallower than one would expect (*Sharpton 1994; Herrick and Sharpton 2000*). The shallow structure of these craters *was* canonically thought to come from volcanic infilling with no major contribution of topographic relaxation. *Grimm and Solomon (1988)* used a gravity-driven relaxation model, and concluded that Venusian craters seem to maintain pristine shape without any significant relaxation. In a recent study, we examined the relaxation of Mead basin using the finite element method with the application of a viscoelastic rheology (*Karimi and Dombard 2017*). Mead is the largest known crater on the surface of Venus with the size of 270 km in diameter. Our results indicated that lower crustal flow is efficient in reducing the topography at the surface and subsurface of Mead basin, and relaxation could play a more important role than presumed before. Previous relaxation model of Venusian craters (*Grimm and Solomon 1988*) suggested that no detectable relaxation occurred for craters, mainly due to i) assumption of a very thin crust, ii) extremely low thermal state, and iii) simple rheological setting. However, due to improvements in our knowledge of Venus, an updated/complex understanding of anhydrous rheology and advancements in computational sciences, I revisited crater relaxation on Venus and now I show that relaxation is efficient. Here, my results show that the viscoelastic relaxation of topography is not only limited to Mead-size craters: smaller size craters (≥50 km) also have the potential of being viscoelastically relaxed under plausible Venusian condition (Fig. 1). *This finding has an important implication and can be used to constrain the background heat flux and atmospheric state of Venus*. In the next step of this study, I plan to examine the relaxation of bright-floored craters on Venus under plausible atmospheric conditions in order to generate a global thermal map of Venus.

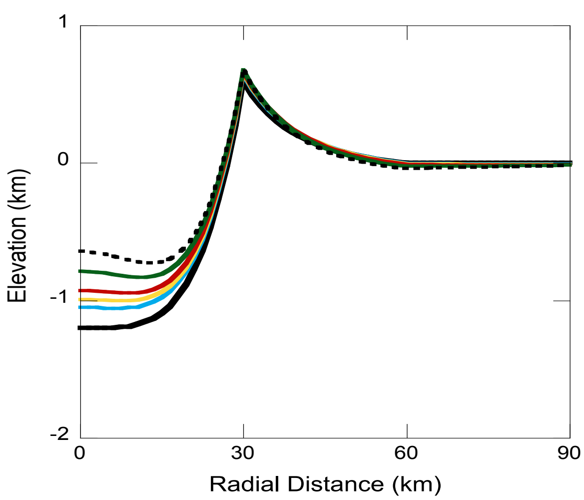

Figure 1. Following the approach of *Karimi et al. 2016* and using finite element analysis, I modeled the deformation of a 60-km crater under various plausible Venusian thermal states over 100 Myr. The figure shows the simulation results for an axisymmetric mesh at the surface. Blue, yellow, red, green and dashed lines show the results of simulations for background heat fluxes of 40, 45, 50, 60 and 70 mW m^{-2}, respectively. Bold black line is the initial shape of the surface topography. We use similar methodology to model the deformation of large bright-floored craters in order to constrain the background heat flux of Venus.

Development of a radiative transfer model for a Venus general circulation model

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Introduction

We have been developing a general circulation model for a various planetary atmospheres. Venus is a one of the targets of our simulation, because of a unique feature of its thick atmosphere. In simulating the Venus atmosphere, one of the moist difficult aspects is radiative transfer calculation. The difficulty is resulted from uncertainties of optical parameters of gases in pressures and temperatures which are different from those in Earth's atmosphere, significantly. However, several recent theoretical and numerical studies have investigated radiation field in Venus atmosphere (e.g., Takagi et al., 2010; Haus et al., 2015; Lee et al., 2016), and radiation models for Venus general circulation models (GCMs) have been developed (e.g., Eymet et al., 2009). In this study, we develop a radiation model which can be applied to a Venus GCM following those previous studies.

Model

In developing a radiation model, a line-by-line model is developed, first. Then, we develop a correlated k-distribution radiation model, which can be used in a general circulation model. The line-by-line calculation is performed with Voigt line profile calculated with Humlicek (1982) method, with a line shape modification based on Perrin and Hartmann (1989) for carbon dioxide absorption lines. Gas absorption line parameters are obtained from HITRAN2012 (Rothman et al., 2013) and HITEMP2010 (Rothman et al., 2010). In addition to line absorption, we include continuum absorptions based on several sources, following previous studies such as Lee et al. (2016). Continuum absorption by water vapor is considered by the use of the MT_CKD model (Mlawer et al., 2012). Continuum absorption by carbon dioxide is considered based on Lee et al. (2016). But, in addition to those, we include a continuum absorption in 8363-9434 cm-1 based on Bezard et al. (2011). This additional absorption improves nighttime spectrum in this wavenumber range. In ultraviolet and visible region, we include absorption by sulfur dioxide.

Results

By the use of this model, we performed line-by-line calculations of radiative flux profiles, radiative spectrum, and albedo under the condition of temperature profile of the VIRA, composition profiles of Crisp (1986) and Pollack et al. (1993), and cloud profiles of Crisp (1986). The results show good agreements with existing observation data. However, the results are sensitive to assumed profiles of composition and clouds. In the presentation, we will present some sensitivity of the model results. Further, we will present a radiative-convective equilibrium temperature profile in a condition of Venus with our k-distribution model.

An experiment to investigate Venus's deep atmosphere.

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The characteristics of the Venus atmosphere closest to the ground are still unknown to a large degree. The only reliable temperature profile measured below 12 km altitude was obtained in 1985 by the VeGa-2 lander (Linkin et al., 1986). This profile, obtained during the ~1h descent, is highly unstable in the lowest 7 km, meaning that the near-constant vertical gradient is steeper than the adiabat, a characteristic that may be explained by a variation of the abundance of nitrogen from 3.5% at 7 km altitude to 0 at the surface, as proposed by Lebonnois & Schubert (2017). The physics of the composition gradient is difficult to understand in the absence of more information, however, considering the observations in a recent experiment (Hendry et al., 2013) it is here conjectured that this gradient could result from gravity effects inducing a density-driven separation of nitrogen and carbon dioxide.

To investigate the behavior of the CO_2-N_2 mixture under conditions ranging from the Hendry et al. (2013) experiment to the near-surface atmosphere of Venus, we have designed an experiment that will be conducted at the Glenn Extreme Environment Rig (GEER) (Kremic et al., 2014), at NASA Glenn Research Center in Cleveland in August 2018. The CO_2-N_2 gas mixture will undergo experimental conditions of 100 bar at various temperatures in a 60 cm vertical steel cylinder with an internal diameter of 8.7 cm. The composition of the gas mixture is measured by gas chromatography at the top, middle and bottom of the vessel, to investigate the vertical composition gradient. To increase the accuracy of the measured abundance of nitrogen, mass spectrometry will also be used. The first step in our experiment is to use the Hendry et al. (2013) experimental conditions, with a mixture of 50% CO_2 / 50% N_2 at 296K and 100 bar, and inquire whether the strong vertical gradient observed in the 18-cm tall Hendry et al. (2013) experimental vessel is reproducible: 70% nitrogen at the top, 10% only at the bottom. Then, fixing the temperature at 310K and the pressure at 100 bar, we will vary the abundance of nitrogen from 50% to 3%, to reach a proportion resembling the Venus atmosphere. In a second phase, maintaining the pressure at 100 bar and the nitrogen abundance at 3%, the temperature will be step-wise increased up to 735K, so as to reach Venus's near-surface conditions. At every step, the vertical gradient of nitrogen in the 60-cm high vessel will be measured.

Results of the experiment will be shown, and their consequences for the lower Venus atmosphere will be discussed.

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Cloud Cover of Venus

The global images returned by the four imaging cameras on Akatsuki orbiter of the day and night side of Venus reveal a very dynamic cloud cover with contrast patterns across wavelengths. Analysis of the limb provides information about the haze layer above the nominal cloud tops from the day side images. The LIR camera images at 8-12 µm yield information about the temperatures at the slant unit optical depth level globally.

It has been known for some time that in reflected light the contrasts peak at about 370 nm and decrease to barely discernible at shorter and longer wavelengths. Sulfur dioxide has been identified as one of the species that is likely responsible for contrasts observed in the 283 nm images from Akatsuki, but other species are required to produce contrasts at wavelengths longer than 330 nm. More than a dozen species have been proposed for explaining the absorption of sunlight, but the identity of the absorber(s) and their nature are still a mystery.

On the night side cloud features seen in the Akatsuki images at 1.74, 2.26 and 2.32 µm are visible due to the spatially variable transmission of the radiation emitted by the lower atmosphere as it escapes to space. What causes these opacity differences is not clear. The morphology of the night side features suggests some influence of local circulation, but given the ubiquitousness of the primary cloud particles (~ 1 µm radius) it is not easy to understand why contrasts exist at all on the day and night sides without considering the local circulations about which we know very little.

There is a growing suspicion that more than two absorbers may be required to understand the contrasts on Venus. The available data are not adequate to confirm whether the other absorbers are gaseous, particulate or even organic. Limaye et al. (2018) have revisited the possibility of life in the clouds of Venus explored whether microorganisms may contribute to the contrasts seen on both day and night side of Venus.

Cloud variations and water vapor abundance near the Venus surface from the night-side windows observations by the SPICAV IR/Venus-Express.

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Venus lower and middle atmosphere is hidden for remote observations by the optically thick cloud layer. The infrared emission escape to space only within several narrow transparency windows located between strong CO_2 absorption bands. Their intensity is modulated by the scattering on the cloud particles and the minor gases absorption below clouds.

Clouds are one of the reasons for the strong greenhouse effect forming the current Venus climate. Their aerosols mainly composed by the H_2SO_4 solution form three layers, upper and lower hazes which are characterized by the size of prevailed particles [1]. The upper layer (50-70 km) and haze (>70 km) contain modes 1 and 2 having corresponding radiuses of < 0.4 and 1 μm [2]. The slightly bigger mode 2' and the most massive mode 3 particles distributed in the middle and lower clouds (46-50 km). The mode 3 (radius of 3-4 μm) particles determine the opacity and bulk of the Venus clouds [1].

The H_2O absorption is presented in 1.1- and 1.18-μm windows which thermal emission originates from the surface and the first scale height (0-15 km) of the atmosphere. The recent ground-based observations and data obtained by SPICAV-IR and VIRTIS of the Venus Express show a water volume mixing ratio varying near the value of 30-35 ppm [3-5] in the lower atmosphere.

The IR channel of the SPICAV instrument covered 5 night windows at 1, 1.1, 1.18, 1.28 and 1.31 μm. The 1.1- and 1.18-μm are sensible to surface emissivity changes, clouds parameters and the water vapor abundance in the deep atmosphere. The intensity of 1.28-μm window is modulated only by variations of clouds parameters. However it is contaminated by an oxygen emission at 1.27 μm produced at 95 km [6] which limits the spectral range of the window under consideration. The 1.31-μm intensity is much weaker than others. The SPICAV IR dataset is extended from 2006 to 2014 years with a good spatial coverage of almost the whole globe. It was reported that the 1.28-μm maximum intensity varied from 0.05 to 0.1 $W/m^2/\mu m/ster$ with slightly higher values for the north hemisphere than for the south one [7]. The modeling allowed to conclude that these variations are determined by opacity changes in lower clouds.

Synthetic spectra of the night emissions were built according to multiple scattering radiative transfer model realized in the SHDOMPP program based on the spherical harmonic discrete ordinate method [8] for plane parallel geometry adopted for the Venus night-side observations in [4, 9]. The temperature-pressure profile was taken from the VIRA database. We take the assumption that the aerosol droplets are of spherical shape and they consist of 75% H_2SO_4 solution. An optical depth, single scattering albedo, asymmetry parameter are calculated using the Mie theory for the cloud distribution described by Haus et al. (2016) [10].

The current work is aimed to analyze the whole dataset of SPICAV observations to retrieve the cloud parameters changes and water abundance at the same time.

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Capricious Cytherean Clouds: The Long and the Short of It

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Variations in the condensational clouds of Venus at altitudes between roughly 45 km and 60 km altitude were first revealed by Allen & Crawford (1984). Understanding these variations was a primary goal of the VIRTIS instrument on Venus Express (Drossart et al., 2007). And these variations are also being leveraged by Akatsuki in a continuing effort to understand the super-rotation of the Venus atmosphere (Nakamura et al., 2016).

We previously characterized the evolution of individual features by using data from VIRTIS-M-IR on Venus Express to quantify the variability of those features (McGouldrick et al., 2012). That work found that individual features evolved on time scales typically of about one day (24 hours), though smaller features were seen to form and/or dissipate on much shorter time scales (as short as the 30 minute cadence of the analyzed data). That work also found that the mesoscale dynamics in the vicinity of the features was consistent with the circulation that would develop in response to convergence and divergence on an Earth-sized planet having a seven-Earth-day rotation period. More recent work found a roughly 150-Earth-day periodicity in the 1.74μm radiance, indicating long-term, periodic, variations in the cloud cover are also present (McGouldrick & Tsang, 2017). These long-term variations were most pronounced at mid-latitudes ($30° - 60°$), but could not be ruled out at equatorial latitudes ($0° - 30°$), due to the observation geometry of VIRTIS. No long-term polar ($60° - 90°$) trends were noted.

In the present work, we build on those previous efforts in two ways. First, we demonstrate a baseline whereby results from VIRTIS (a medium-resolution imaging spectrometer) can be quantifiably compared with images through the several filters of the IR2 camera on Akatsuki. Next, we quantify the physical changes in the clouds that are observed at different times of high or low overall cloud opacity, and attempt to leverage this information to produce a reasonable picture of both long- and short-term cloud evolution in the constantly changing, capricious, clouds of Venus.

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Abstract for IVC 2018
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Venus IR2 Image Reduction (RS, RD and RDS) and its Scientific Outcomes

IR2 onboard Akatsuki, imaging night-side of Venus, is known to detect infrared radiation originating from the lower atmosphere, visualizing middle to lower clouds of Venus (~45 – 55km) at wavelengths 1.735, 2.26 and 2.32 microns. Since very intense dayside crescent is always adjacent to the night-side, contamination by spreading light from the dayside is unavoidable and affects the photometry. Such contamination was found to be more serious than was anticipated before the launch. Examination of pre-launch IR2 H-band image reveals the point spread function (PSF) of multiple exponentially decaying halation rings around the brightness core (Satoh et al. 2017). Such PSF is due to the multiple internal reflections of infrared light in the Si substrate of the IR2 detector (PtSi) and was best approximated by a modified Moffat function.

An effective application of such PSF is to invert the contamination process, restoring the contrast of night-side image to a level that can be used in photometric studies. Two methods were initially developed for reducing the IR2 images from dayside contamination i.e. "Restoration by Subtraction" (RS) and "Restoration by Deconvolution" (RD). The RD method was improved by implementing updated PSF and optimum F factor (Dayside brightness seed). Furthermore, analysis have shown that there is residual dayside model brightness of ~10% near the terminator which was then being subtracted from the deconvolved image. Hence, "Restoration by Deconvolution and Subtraction" (RDS) was applied to suppress dayside influence close to the terminator. However, RD method shows discrepancies in 1.735 window analysis, where RS may be more applicable. The degree of photometric accuracies for all method choices will be evaluated and their applications to extract photometric information at near-dusk and near-dawn will be implemented for physical studies.

Scientific outcome of the photometric correction can be used to study more accurately the local time variation, and the averaged wind vector near the terminator can be used to compare with wind speeds in the night side. Furthermore alongside the radio occultation measurements, characterising the gravity waves near the terminator can constrain the static stability profile in the convective layer. The time constant of mode transition (day to night) can also be determined. Finally, particle mode size distribution from correlation map between I(1.74um) and I(2.26um) (Carlson et al. 1993) will be investigated with photometric accuracies in both observation windows where the cloud microphysics in the lower and middle clouds can be studied.

Abstract for IVC 2018

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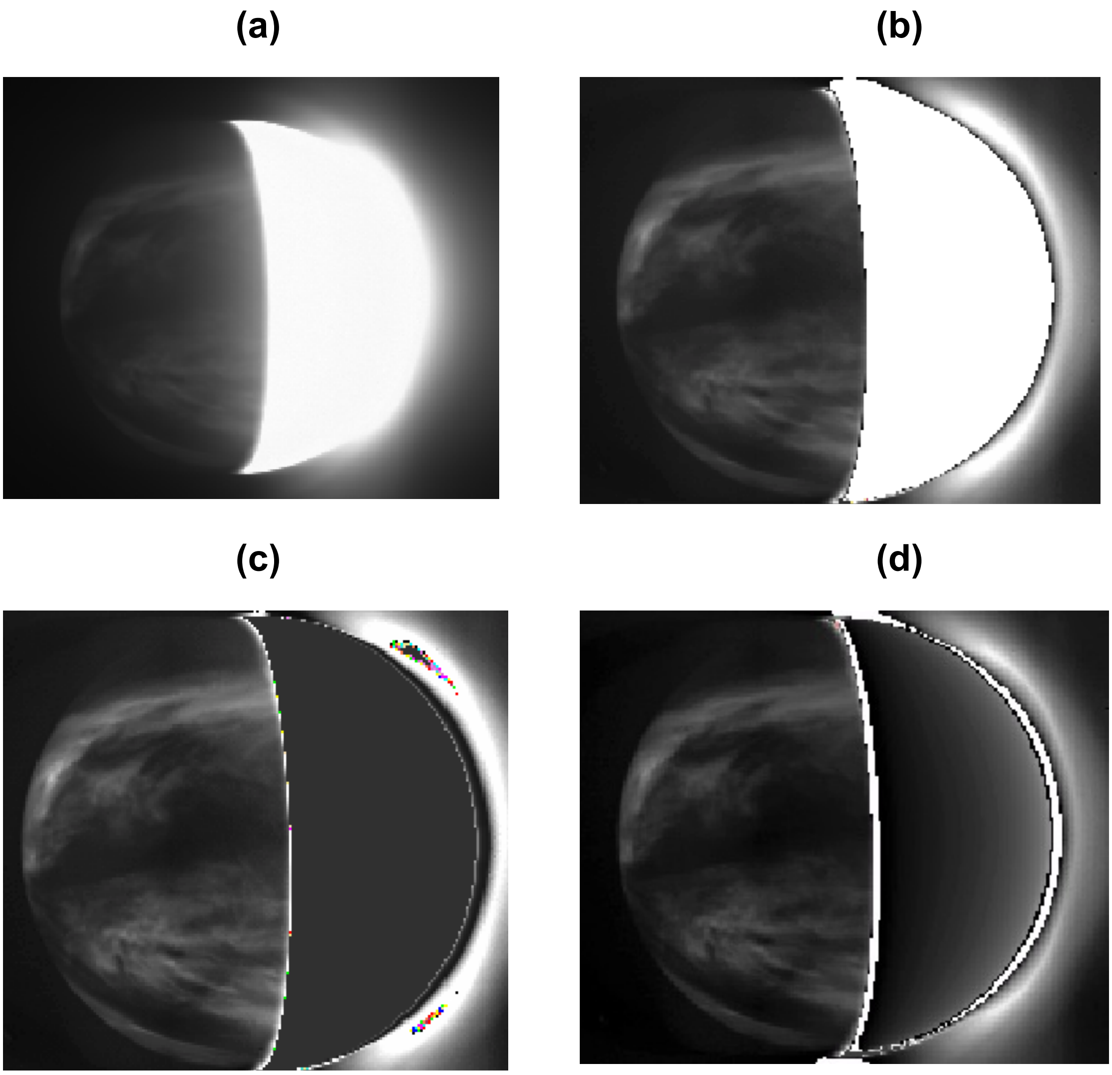

Figure 1 – Venus IR2 (2.26um)

(a) Original Image (b) Restoration by Subtraction (RS) (c) Restoration by Deconvolution (RD) (d) Restoration by Deconvolution and Subtraction (to be revised)

Title: Akastuki Team's Supporting System for Coordinated Venus Observations

(POSTER)

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Abstract:
Akatsuki's mission extension has been confirmed to be until 2020 Japanese fiscal year (March 2021). This period spans two instances of Venus' inferior conjunctions in October 2018 and June 2020. Around the time of inferior conjunctions, nightside observations are possible from the ground. This can aid the lost ability of Akatsuki owing to the unexpected pause of IR1 and IR2 cameras' operations, imaging through the atmospheric windows around 0.9-1.0, 1.7, and 2.3 μm. In addition, Earth-based observations have huge potential to improve our understanding of Venus' atmosphere, complementing Akatsuki's observations. Thus, the Akatsuki Science Working Team (SWT) is endorsing and requesting supporting Earth-based Venus observations that can fill spectral gaps between UVI (283 and 365 nm) and LIR (10 μm) of Akatsuki, and extend the spectral range of day and nightside observations longward up to sub-mm and dayside observations shortward down to EUV wavelengths in the time frames around the upcoming inferior conjunctions, spanning ~20 months in total (June 2018-March 2019 and January-October 2020). These data may be used to investigate many science problems. For one, thermal structures can be retrieved from these data that can be compared with RS/Akatsuki; despite having lower vertical and spatial resolutions, these data can expand the spatial coverage beyond that obtainable by Akatsuki. Similarly studies of winds and chemistry may be completed. Thus, the SWT strongly desires that similar and different hemispheres of Venus are observed concurrently using different viewing geometries from the spacecraft and the Earth, so that Venus' global atmosphere is thoroughly explored during both inferior conjunction periods. And, it is strongly desired that the broadest range of wavelengths is sampled whenever spatially and/or temporally concurrent observations may be obtained by the Akatsuki spacecraft and any available observing platforms; ground-based telescopes, aircrafts, balloons, suborbital/orbital/Venus-flyby spacecraft. Therefore, we have prepared a supporting system for the coordinated Venus observations with Akatsuki, regardless whether observers are the Akatsuki team members or not. We would like to introduce the detailed process, which can be found in the Google doc: (https://docs.google.com/spreadsheets/d/13xnrj39wwZCSnYjLf9QokpIMT8SfurBvhG5UVWUmRk0/edit?usp=sharing) and the website (https://akatsuki.matsue-ct.jp/).

Joint SPICAV/VIRTIS observations of the UV albedo of Venus

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Venus clouds possess high spherical albedo (70-80%) in the visible spectral range, and the planet disk looks very bright and homogeneous. On the other hand, the ultraviolet (UV) albedo is 2-3 times lower and the clouds appear to be very contrasted. The dark spots point out to presence of some cloud components that absorb solar radiation at wavelengths from 250 to 400 nm. One of molecules is sulfur dioxide (SO_2), which varies from 0.1 to 1 ppm at the cloud top [1, 2]. Other candidates are also sulfur-bearing species, sulfur S_x with different valences [3], OSSO [4] and even $FeCl_3$ [5]. So far, there was no published precise measurement of Venus albedo in spectral range 200-400 nm that would allow retrieval the unknown UV absorbers of Venus clouds.

In the present work we perform data processing from two spectrometers that measured UV albedo of Venus clouds onboard the Venus Express (VEX) orbiter in 2006-2014. The UV channel of SPICAV operated at 115-320 nm [6], while the UV-VIS channel of VIRTIS covered 300-1000 nm [7]. We have selected a few tens of simultaneous nadir observations with similar pointing that allows us combining the clouds reflectance spectra at 200-400 nm. At the moment, spectral and absolute radiance calibrations are being performed for correct merging of spectra between two spectrometers.

Coauthors from IKI acknowledge support by the Ministry of Education and Science of Russian Federation grant #14.W03.31.0017.

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The Venus AFES LETKF Data Assimilation System (VALEDAS)

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The Venus AFES (Atmospheric GCM for the Earth Simulator) LETKF (local ensemble transform Kalman filter) Data Assimilation System (VALEDAS) was developed to make full use of the observational data. The system uses the Venus AFES for forecasts and the LETKF for data assimilation. To examine the validity of the system, two datasets were assimilated separately into the Venus AFES forecasts forced with solar heating that excludes the diurnal component Qz; one was created from the Venus AFES run forced with solar heating that includes the diurnal component Qt, whereas the other was based on observations made by the Venus Monitoring Camera (VMC) onboard the Venus Express. The VALEDAS rapidly reduced the errors between the analysis and forecasts. In addition, the VALEDAS successfully reproduced the thermal tide excited by the diurnal component of solar heating, even though the second datasets only included horizontal winds at a single altitude on the dayside with a long interval of approximately one Earth day (figure). Currently, Ensemble Forecast Sensitivity to Observations (EFSO) technique was implemented to quantify how much each observation improves the Venus AFES forecasts. The system would be useful to produce reanalysis from the Venus Climate Orbiter 'Akatsuki'.

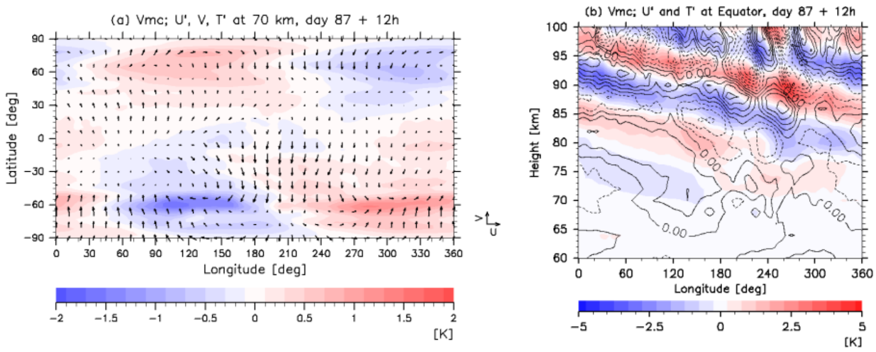

Figure: (a) Horizontal and (b) vertical distributions of temperature deviation obtained by VALEDAS. Real observations based on the VMC are assimilated.

[Reference]

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Towards a (GCM-based) Venus Climate Database

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Introduction

Over the past twenty year, our team, with support from the European Space Agency and CNES (French space agency) and collaboration with other European partners, has successfully developed, maintained and distributed the Mars Climate Database (MCD) [1] to the international community. This database is derived from dedicated Global Climate Model (GCM) developed by our consortium.

The Venus atmosphere is also studied by our planetary atmospheres team, using a state of the art Venus GCM [2-4]. Based on our experience with Mars, we feel that the best means to share these results with the international community, both for users wanting to compare with their models or analyze observations and users planning future missions, would be with the creation of a Venus Climate Database (VCD).

Overview of the Venus Climate Database contents and access modes

Based on our experience with the MCD, the VCD would:

- Be based on the latest validated outputs of our Venus GCM.
- Provide an interface routine (e.g. Fortran, but also with interfaces in other languages such as C, Python, etc.) so that a user could easily retrieve atmospheric fields (temperature, wind, pressure, …) at any sought coordinate in space and time.
- Provide an online interface (similar to the MCD one: http://www-mars.lmd.jussieu.fr/) for users interested in obtaining a quick look at the data.
- Provide some access to the VCD as a virtual observatory in the frame of the Virtual European Solar and Planetary Access (VESPA) [5] Europlanet 2020 Research Infrastructure program (http://www.europlanet-vespa.eu/).

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Long-term variation of super rotation seen in Akatsuki observations

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Abstract:

Based on Venus Monitoring Camera (VMC) observations onboard Venus Express, it has been reported that the super-rotation of Venus atmosphere at the cloud top level showed temporal variations with a time scale of Venusian year (224 Earth days) whose peak-to-peak amplitude was 20 m s^{-1} (Kouyama et al., 2013), and decade-scale variation in which the super rotation increased 30 m s^{-1} over 6 years (Khatunsev et al., 2013). Since the amplitude of the variations reached 30% of the typical zonal wind speed of the super-rotation (100 m s^{-1}), there should be active momentum transportation in Venusian atmosphere and/or variation of dynamical state of the atmosphere with the time scale.

To continue monitoring the variation, we have measured wind speed at the cloud top level based on Akatsuki UVI observations with a newly developed cloud tracking technique (Ikegawa & Horinouchi, 2016; Horinouchi et al., 2017) since Akatsuki's Venus orbiter insertion (VOI-R). To extract the temporal variation more clearly, we reduced local time dependence in zonal winds by measuring deviation of zonal wind speed in each observation from zonal wind speed at a reference day (= 400th day since VOI-R) with respect to each local time. As seen in VMC observation, the smoothed zonal wind speed showed ~10 m s^{-1} variation within 100 days, and it increased and decreased alternately (Figure 1). Topographical dependence in the zonal wind speed seemed to be not clear in this period.

Since momentum transportation by planetary scale waves or variation of thermal condition may affect the variation of zonal wind speed, we will also show the temporal variation of planetary scale wave signatures seen in wind speeds and thermal tide components.

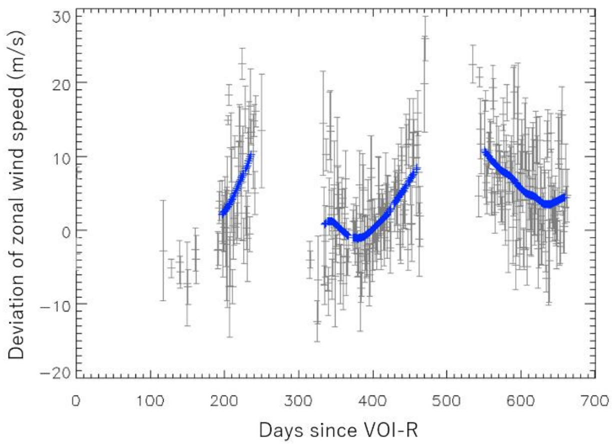

Figure 1. Temporal variation of zonal wind speed at the equator in Akatsuki observation. Blue lines are the time series smoothed by a Gaussian filter.

Cloud movements in the Venusian Atmosphere

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This paper examines cloud movements in the Venusian atmosphere based on data collected during various Venus missions. Cloud dynamics and cloud density of the clouds are discussed. Data from the Venus Climate Orbiter, also known as *Akatsuki*, is utilized in studying thermal emissions in the atmosphere. The formation of eddies and cyclones are considered in the atmospheric modelling of Venus and correlated with the absence of the magnetic field of the planet. Data from sensors onboard *Akatsuki*, such as the Lightning and Airglow Camera, as well as the results of our analysis of physical phenomena, may help in verifying the results of this work. Using the known densities of atmospheric constituents, and applying the principles of viscosity and fluid dynamics, questions regarding the super-rotation of clouds in the atmosphere of Venus shall be answered. The movement of clouds in the westward direction will be studied with respect to the planet’s gravity. Finally, an overall cloud movements in the atmosphere of Venus will be discussed along with the possible causes of lightning.

Title:
Doppler-wind observations of Venus mesospheric circulation: Revisiting previous dataset and comparing with new GCM experiments

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Abstract:

Atmospheric dynamics of Venus' mesosphere (~70 – 120 km in altitude) still remains as a puzzle. There are several observations of mesospheric wind (more precisely, velocity of the wind projected on the line-of-sight of observation) at ~95–110 km, derived from Doppler-shift measurements of CO spectra at millimeter- and submillimeter wavelengths, which show the presence of strong temporal variation [e.g., Lellouch et al., 1997, 2008; Clancy et al. 2012]. The first attempt to interpret those observations was to consider the mesospheric global circulation as a linear combination of two wind regimes: super-rotating retrograde zonal flow (hereafter, RZ) and a subsolar-to-antisolar flow (SSAS). The former wind regime is well known as the global circulation of the Venus troposphere, and the latter is often discussed as a circulation in the upper thermosphere where a large thermal gradient between day and night exists. The mesosphere which lays between the troposphere and thermosphere has been considered as a dynamically transient region from RZ to SSAS. However, not a few results of observed Doppler-wind, particularly those of spatially-resolved maps from interferometer observations, cannot be sufficiently explained by such a simple combination of RZ and SSAS [e.g., Moullet et al., 2012].

A new interpretation was proposed by Hoshino et al. (2012, 2013) after the development of a new Venus upper atmospheric general circulation model (GCM). One of the key achievements of their GCM is the inclusion of vertical propagation of gravity waves, and the wind data obtained by their GCM showed a qualitative representation of one of previously observed Doppler-wind maps which has been unexplainable by the simple combination of RZ and SSAS. Recently, Gilli et al. (2017) developed another GCM which uniquely covers from the ground to thermosphere, and succeeded in obtaining an overall agreement with the thermospheric temperature profiles measured by Venus Express and some ground-based instruments.

This presentation revisits past observational dataset of Doppler-wind taken at a variety of the local times of Venus, and compares them with numerical experiments of recently developed GCMs.

Akatsuki (space-based cloud-tracking) and TNG/HARPS-N (ground-based Doppler velocimetry) coordinated wind measurements of cloud top Venus' atmosphere.

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Abstract

We present wind velocity results based in the measurements of the horizontal wind field at the cloud top level of the atmosphere of Venus, near 70 km altitude, in the visible range on the dayside. At this altitude the wind circulation is dominated by the retrograde zonal superrotation (RZS).

The cloud-tracking space observations were carried out, between 26-31 January 2017, by the "Ultra Violet Imager" (UVI) onboard Akatsuki's Venus Climate Orbiter (VCO), using the 365 nm filter. The cloud-tracking technique we used was evolved from a phase correlation method between images developed by Peralta et al. 2007. The use of UVI images to track cloud features from the unknown UV absorber has already provided important results in the constrain of zonal and meridional wind at cloud-top (Horinouchi et al. 2018).

The ground observations were carried out, on the 28th and 29th of January 2017, at the 3.58-meter "Telescopio Nazionale Galileo" (TNG) using the "High Accuracy Radial velocity Planet Searcher" spectrograph (HARPS-N) in the visible range (0.38-6.9 µm). It was the first use of this high-resolution (R≈115000) spectrograph to study the dynamics of a solar system atmosphere. The sequential technique of visible Doppler velocimetry is based on solar light scattered by cloud top particles in motion. This technique was developed over the last decade (Widemann et al. 2008, Machado et al. 2012, 2014) and has proven to be a reference technique in the retrieval of instantaneous zonal and meridional winds (Machado et al. 2017). In this work we successfully adapt this technique to the HARPS-N fiber-fed spectrograph with consistent results.

The Akatsuki/UVI observations provided 3 high-quality images per observation day, separated by ~2h interval. Due to its low inclination orbit (<10º), Akatsuki's images offer a great range in Venus' dayside, allowing us to track cloud features from 60º N to 70º S latitude and from 7:30 to 17:00 local time. This has enable a study of spatial and time variability of both zonal and meridional wind. The HARPS-N ground observations focused on the meridional wind field between 60° S and 55° N latitude and zonal wind field near equator (latitudes between 10° S and 10° N). HARPS-N results present an unprecedented high-precision meridional wind latitudinal profile.

This work intends to contribute to the characterization of Venus' cloud top zonal and meridional wind by studying latitudinal behavior on hour and day timescales as well as wind temporal and spatial variability. Similar studies have proven the relevance of both space-based cloud tracking observations (Sánchez-Lavega et al. 2008, Hueso et al. 2012, Hourinouchi et al. 2018) and ground-based doppler velocimetry (Machado et al. 2014, 2107), as well as the usefulness of coordinated observations in the cross validation of both technique results.

Influence of the local time and Aphrodite Terra topography on the cloud top circulation from VMC/Venus Express imaging

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Abstract

Winds derived by digital tracking technique from UV (365 nm) images captured by the Venus Monitoring Camera onboard Venus Express spacecraft from 2006 through 2013 were used to study the atmospheric circulation at the cloud tops (70±2 km). This data set allows studying both variations of the wind speed with latitude and longitude (correlation with surface topography) and their dependence on local time. The zonal deceleration was found above Aphrodite Terra, one of the largest highlands in the equatorial region on Venus. The wind speed decrease appears to be a solar-related feature and peaks at noon above Aphrodite Terra with zonal wind pattern resembling topography of the highland. The area of slow zonal wind extends at least up to 30°S. At the same time the wind speed increases by approximately 5 m/s to 30°S, and the area of decelerated wind shifts in the direction of superrotation. The minimum of zonal wind velocity is also observed at noon above Ovda Regio - the highest region of Aprodite Terra highlands. In contrast, above lowlands the zonal wind pattern appears to be independent on local time. We attribute the observed deceleration of the zonal wind to the effect of breaking gravity waves induced by the surface highlands. We also suggest that solar flux can penetrate deeper in the atmosphere at noon that results in heating of the upper cloud layer and increasing of the atmospheric stability, that enables more efficient the propagation of gravity waves through the cloud layer.

Observing upper atmospheric gravity waves on Venus using polarimetry

Gourav Mahapatra[1], M. Rodenhuis[2], L.C.G. Rossi[1], D.M. Stam[1]

There is ample evidence for gravity wave activity on Venus. Indeed, waves with various extensions have been observed through direct imaging (e.g. Venus Express and Akatsuki images) as well as through in-situ measurements (e.g. with the Pioneer Venus-ONMS instrument). Indeed, Venus's middle and upper atmosphere has long been expected to support gravity waves with wavelengths ranging from 100 to 600 km (Kasprzak et al., 1988). The properties of gravity waves depend on the atmospheric structure and on the thermal and dynamical interactions within the atmosphere. Detecting and characterizing them both on Venus's day-side and night-side would improve our understanding of our still enigmatic neighboring planet.

Gravity waves influence the local atmospheric density structure. The density variations in the thin atmosphere above the clouds will be quite small, and very challenging to detect with flux measurements of e.g. reflected sunlight, in particular because the bright, underlying clouds will completely dominate the signal. Here we show that the linearly polarized flux of the reflected sunlight, however, is sensitive to such local density variations in the thin atmosphere gas above the clouds, and that the change in the degree of polarization P due to density variations is relatively independent of the polarization signal of the underlying clouds. Accurate polarimetry could thus be used as a tool to detect and characterize gravity waves.

We explore the existence and characteristics of high-altitude gravity waves using the numerical scheme CLAWPACK (LeVeque et al., 2013; Snively and Pasko, 2008). We model the Venus atmosphere as a 2D-planar, finite element grid and place an oscillating momentum source at an altitude of 55 km to trigger gravity waves. We find only a certain range of frequencies to allow the free propagation of gravity waves, consistent with previous model predictions (Mayr et al., 1988). We model the effects of atmospheric density fluctuations due to such waves on the total and polarized flux using an adding-doubling radiative transfer code (de Haan et al., 1987). Our simulations confirm that small variations in gaseous density due to gravity wave activity leave a variation on the order of $\sim 10^{-3}$ in P across Venus's illuminated and visible disk.

In addition to the simulations, we present observations of Venus's disk taken with the high-precision ExPo (Experimental Polarimeter) instrument (Rodenhuis et al., 2008) on the William Herschel Telescope in La Palma. The polarization shows a concentric ring pattern extending across the disk. The rings are invisible in the reflected flux observations that were taken simultaneously. Physical reality of the observation is still under investigation but no obvious instrumental/data reduction errors has been found yet. Our simulations of the gravity waves, the corresponding density variations, and the related polarization variations, suggest the rings are possible due to gravity waves above the Venus clouds. Follow-up polarization observations (with another instrument as ExPo has been dismantled) are necessary for confirming the rings in polarization and the use of polarimetry for detecting and characterizing gravity waves in the atmosphere of Venus and other planets.

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Cosmic rays detected by LAC on board Akatsuki

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The high energetic particles pass through our solar system, which is called as cosmic-ray, mainly originates from the outside of the system. On Venus, since the planet does not have geomagnetic shields, cosmic-ray ionize the atmosphere, and this effect is considered as a dominant ionization source. Meanwhile, we have known that some bodies within the solar system shine to X-rays, and in the case of Venus, charge exchange interactions between highly charged ions in the solar wind and the Venusian atmosphere would be one of the X-ray sources.

Our understanding of the environment of the high energetic particles around Venus orbit is still insufficient. Therefore, the detection of cosmic rays by an instrument onboard Venus orbiter provides us precious information. Lightning and Airglow Camera (LAC), which is one of the onboard instrument of Akatsuki, is a new type of lightning detector equipping 8×8 pixels of 2x2mm APD (avalanche photodiode) detector and enables detecting optical lightning flash with 30 kHz sampling rate. LAC adopt the pre-trigger sampling method to record pulsed signal, and over 300 of cosmic-ray events were observed during the sixteen times of entire LAC operations from Aug 2016 to Aug 2017.

The estimated average event rate of LAC was 0.0048 /events/min/mm^2. Since, the previous detection by Pioneer Venus star sensor [Burucki et al., 1981; 1991] was 0.28 (or 0.12 during quiet sun) events/min/mm^2, this low event rate might be caused by the LAC shielding is much less susceptible to cosmic ray triggers than PVO. The output peak values of the pulsed signals have covered almost from 6 digits to 80 digits. Since the energy of cosmic-ray is high enough to excite photo-electron inside the detector, this wide range of the peak values can be caused by the incidence angle of cosmic rays to the face of APD detector. Under this assumption, the possibility of the incidence angle (θi) is proportional to sin2θi when we expect the isotropic cosmic ray incidence. We conducted stoical analysis using over 300 data of cosmic ray event and found that detected cosmic rays roughly follow the assumed isotropic incidence relation (Fig. 1). The dependence of event rate on Venus Spacecraft distance was investigated as Fig. 2. However, it was not obvious that the slightly low event rate was confirmed around 13000 and 17000 km. This kind of distance dependency could represent the specific source on Venus, but it should be noted that the LAC shielding makes X-rays difficult to pass through the detector.

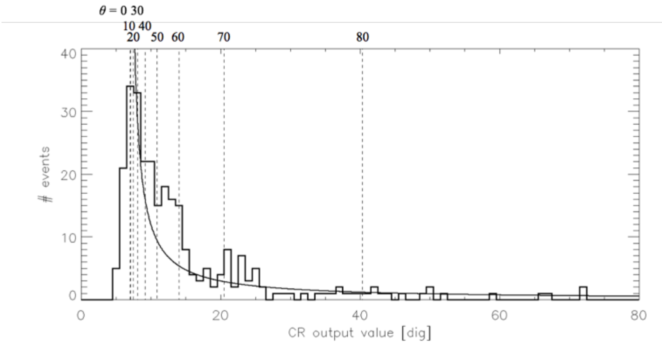

Fig 1: Cosmic-ray event distribution in the maximum recorded signal levels. The solid line shows the expected event number assuming the particle isotropic incidence, and the vertical dashed lines show the representative incidence angle in a interval of 10 degree.

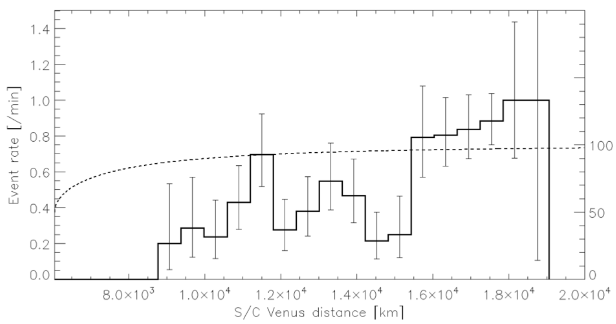

Fig 2: Event rate distribution in a distance from the center of Venus and spacecraft. The dashed line shows the percentage of the solid angle occupied by Venus disk at each distance.

Airglow emissions, such as NO and O2, have been observed previously on Venus. They provide insights into chemical and dynamical processes that control the composition and energy balance in the upper atmosphere. The OH airglow emission has been observed previously only in the Earth's atmosphere which was discovered (Meinel 1950) in high-resolution spectra of the Earth's atmosphere and were successfully modeled by Pickett et al. (2006). Similarly, Venus airglow emissions have been unambiguously detected in the wavelength ranges of 1.40-1.49 and 2.6-3.14 μm in limb observations by the Visible and Infrared Thermal Imaging Spectrometer (VIRTIS) on the Venus Express (VEX) spacecraft. These emissions are attributed to the OH (2-0) and (1-0) Meinel band transitions as well (Piccioni et al., 2008). The integrated (slant path) emission rates for the OH (2-0) and (1-0) bands were measured to be 100±40 and 880±90 kR respectively, both peaking at an altitude of 96±2 km near midnight local time for the considered orbit. Photochemical (Caltech/JPL KINETICS) and GCM (VTGCM) model calculations suggest the observed OH emission is produced primarily via the Bates-Nicolet mechanism, as on the Earth, although the Venus background atmosphere is different than that of the Earth. The models are able to distinguish relative contributions due to different key photochemical reactions that contribute to observed features from the VEX VIRTIS data.

Volume emission rates (VERs) are calculated first within the KINETICS and VTGCM codes (photons/cm3/sec) as a summation of the contributions from each OH vibrational level, following a single quantum cascading scheme. We are then able to obtain slant emission rates (MR) which are calculated by multiplying the VER by the local scale height at a given tangent path level along the line of sight in the atmosphere. We compare the results of these calculations and compare with the Soret et al. (2012) analysis of the Venus Express observations and discuss implications of interesting aspects of the data modeling effort.

Radio scintillation during Venusian atmospheric occultations by Akatsuki

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Abstract:
We report the results of radio scintillation measurements conducted by Venus climate orbiter, Akatsuki. Radio scintillation observed during occultations of a planetary atmosphere, which results from the atmospheric diffractions of radio waves emitted from a spacecraft, includes information on the small-scale density and/or temperature structures in the planetary atmosphere. We have analyzed eighteen time series of radio signal intensity scintillations during Akatsuki radio occultation measurements since March 2016. After removing linear trends and refractive defocusing effects from the time series of the radio signals, several Hz wave-like structures remained in the residual attenuation of the radio signal (Figure 1). The duration of the wavy structures corresponds to the altitude range of 70-85km in the upper atmosphere of Venus.

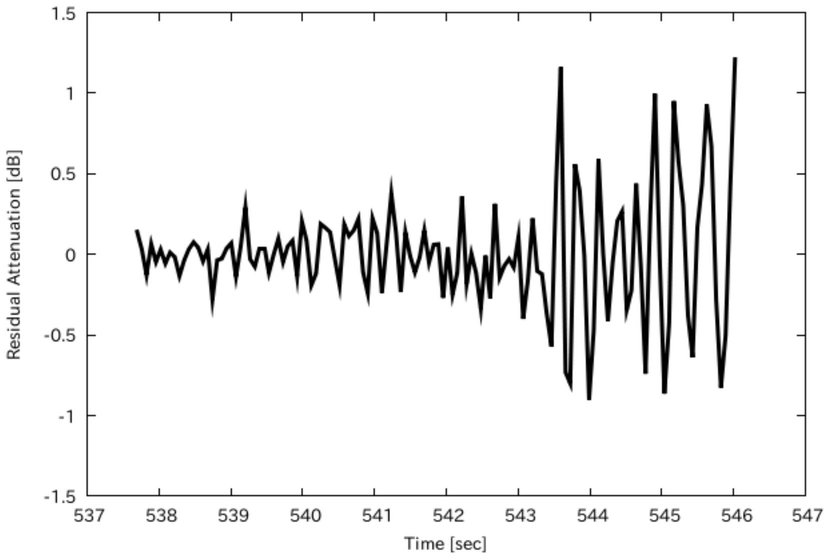

Figure 1: Residual attenuation observed during Akatsuki's radio occultation on 6 February 2017.

Venus Express radio occultation observed with the Planetary Radio Interferometry and Doppler Experiment (PRIDE)

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The Planetary Radio Interferometry and Doppler Experiment (PRIDE) is a technique that can be used to enhance multiple radio science experiments of planetary missions. By 'eavesdropping' on the spacecraft signal using radio telescopes from different Very Long Baseline Interferometry (VLBI) networks around the world, the PRIDE technique provides precise open-loop Doppler and VLBI observables [1],[2]. The application of this technique for atmospheric studies has been assessed by observing ESA's Venus Express (VEX) during multiple Venus occultation events between 2012 and 2014 [3]. From these observing sessions density, temperature and pressure profiles of Venus neutral atmosphere have been derived.

With this VEX test case, we have demonstrated that the PRIDE setup and processing pipeline is suited for radio occultation experiments of planetary bodies [3]. Figure 1 shows an example of the refractivity, neutral number density, temperature and pressure ingress profiles of Venus' neutral atmosphere from the Doppler frequency residuals from the 12-m Katherine (Australia) and 32-m Badary (Russia) and the Doppler residuals of Estrack's New Norcia (NNO), from ESA's Planetary Science Archieve (PSA). Despite the fact that both NNO and Badary have similar antenna dish sizes, with Badary the spacecraft signal is detected down to a lower altitude. The profiles corresponding to Badary and Katherine were derived from the open loop Doppler data obtained with the PRIDE setup, while the profiles of NNO were derived using the frequency residuals obtained from ESA's PSA, corresponding to close loop Doppler tracking data. The advantage of using open loop Doppler data for radio occultation resides in the ability of locking the signal digitally during the post-processing. This allows the estimation of the frequency of the carrier tone at the deeper layers of the atmosphere.

As demonstrated with the detection of Badary, open-loop Doppler data as the one produced with PRIDE allows sounding deeper layers of planetary bodies with thick atmospheres when compared to closed-loop Doppler data. The main advantage of open loop data for radio occultation experiments is that during the post-processing the frequency of the carrier signal can be estimated with precision wideband spectral analysis, even if there are large unexpected changes in the carrier frequency due to, for instance, large refractivity gradients in the deep atmosphere or interference effects such as multipath propagation. This is not the case with closed-loop detections, where in case of large unexpected changes in frequency, the signal goes out of lock. With the wideband spectral analysis of PRIDE, we showed that even with small antennas, such as the 12-m Katherine, the signal can be detected below Venus' clouds layer.

We are currrently working on improving the model of the atmospheric observations to evaluate the impact of the physical assumptions into the the data processing. This covers new challenges such as modeling Venus' atmosphere as an axis-symmetric atmosphere instead of an spherical atmosphere when processing radio occultation observations, and taking into account gradients in the major constituents (carbon dioxide and nitrogen) of the composition of Venus atmosphere (based on observations by [5]) from the surface to the cloud level.

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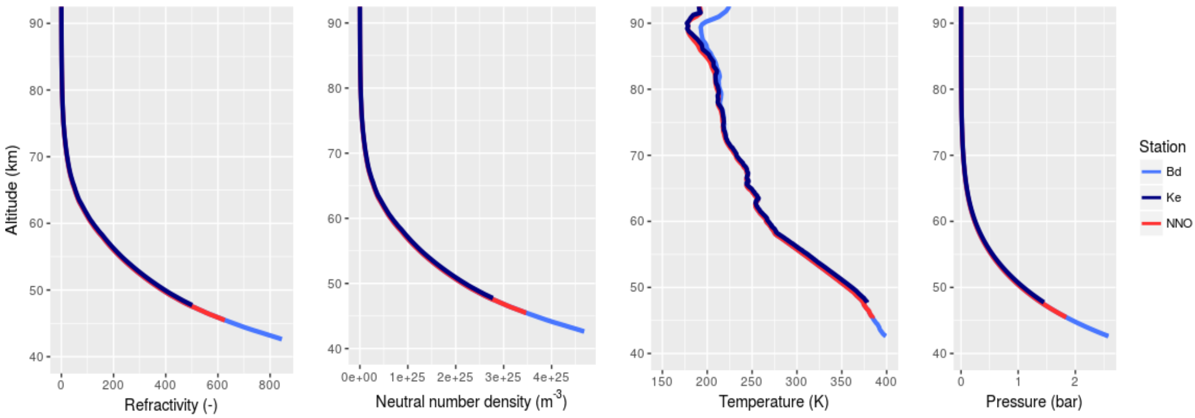

Figure 1: Refractivity, neutral number density, temperature and pressure profiles of the 2012.04.29 session. The profiles corresponding to the 32-m Badary (Bd) and 12-m Katherine (Ke) were derived from the open loop Doppler data obtained with the PRIDE setup, and the profiles of the 35-m NNO were derived using the frequency residuals obtained from ESA's PSA, corresponding to close loop Doppler tracking data.

Small-scale disturbances in the lower dayside ionosphere of Venus

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The Venus Radio science Experiment VeRa on board Venus Express sounded the ionosphere and lower neutral atmosphere of Venus from 2006 to 2014. More than 800 vertical profiles of the ionospheric electron density, neutral atmospheric pressure/density and temperature were derived from occultation ingress and egress observations. A subset of the VeRa ionospheric dayside observations contains small-scale ionospheric excess electron densities in and below the secondary ionospheric layer (Pätzold et al., 2009). A similar feature was identified in the Mars dayside ionosphere (Pätzold et al., 2005). Certain aspects of the Martian excess electron densities indicate that the ionization of the locally available neutral atmospheric species by shorter solar X-ray radiation seems to play a key role in their formation (Peter 2018). This work provides a statistical evaluation of the occurrence rates of the small-scale ionospheric features in the dayside ionosphere of Venus. Correlations between the occurrences of the excess electron densities and observational/environmental parameters (e.g. solar zenith angle, solar X-ray proxies) should reveal if a formation process similar to that in the Martian ionosphere is possible.

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SULFURIC ACID VAPOR IN THE ATMOSPHERE OF VENUS AS OBSERVED BY THE VENUS EXPRESS RADIO SCIENCE EXPERIMENT VERA

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The main cloud deck within Venus' atmosphere, which covers the entire planet between approx. 50 and 70 km altitude, is believed to consist mostly of liquid sulfuric acid. The temperature below the main clouds is high enough to evaporate the H_2SO_4 droplets into gaseous sulfuric acid forming a haze layer which extends to altitudes as deep as 35 km. Gaseous sulfuric acid in Venus' lower atmosphere is responsible for a strong absorption of radio waves as seen in Mariner, Pioneer Venus, Magellan and Venera radio science observations. Radio wave absorption measurements can be used to derive the amount of H_2SO_4 in Venus' atmosphere. The radio science experiment VeRa onboard Venus Express probed the atmosphere of Venus between 2006 and 2015 with radio signals at 13 cm (S-band) and 3.6 cm (X-band) wavelengths. The orbit of the Venus Express spacecraft allowed to sound the atmosphere over a wide range of latitudes and local times providing a global picture of the sulfuric acid vapor distribution. We present absorptivity and H_2SO_4 profiles derived from X- and S-band signal attenuation for the time of the entire Venus Express mission. More than 600 H_2SO_4 profiles show the global sulfuric acid vapor distribution covering the northern and southern hemisphere on the day- and night side of the planet. A distinct latitudinal H_2SO_4 gradient and a southern northern symmetry are clearly resolved. Observations over 8 years allow the study of long-term variations. Indications for temporal H_2SO_4 variations are found, at least at northern polar latitudes. The results shall be compared with observations retrieved by other experiments (VIRTIS, SPICAV) onboard Venus Express as well as with previous observations like Mariner, Pioneer Venus and the Magellan spacecraft.

Venus' atmospheric ion escape rate dependence on upstream solar wind conditions

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How has Venus atmosphere evolved through time? Non-thermal escape from Venus is an important process for determining the Venusian atmospheric evolution [Futaana et al., 2017]. For example, the escape rate during extreme solar wind conditions was found to increase by a factor 1.9 [Edberg et al., 2011]. In this study, we qualitatively determine the correlation of the escaping heavy ion flux from Venus with solar wind density, velocity, and solar EUV flux, and formulate the escape rate as a function of upstream parameters.

We use the Ion Mass Analyser (IMA) instrument, a part of the ASPERA-4 (Analyser of space plasma and energetic atoms) package [Barabash et al. 2007] on board Venus Express (VEx) [Svedhem et al. 2007]. The IMA instrument has a 2π sr field-of-view, with a capability of discriminating the energy per charge in the range of 0.01-36 keV/q. It can also resolve the mass per charge (1 - >40 amu/q). The VEx spacecraft had a 24 h polar orbit with a nominal pericentre at 250 km, during 2006-2014. This orbit structure gave more than 3000 orbits, making it suitable for our parametric study on the outflow and escape from Venus' atmosphere.

We will calculate the velocity distribution functions from the measurements and make average distribution functions in the Venus' magnetotail. The averages will be made by binning the data into spatial coordinates and upstream conditions. The average distribution functions are then used to calculate the total escape rate for each upstream condition. The binning of the spatial coordinates and upstream conditions will be carefully examined in order to ensure the balance between a good measurement coverage of the average distribution functions.

This formulation will allow extrapolation back in time until ~4 Ga when the solar wind and solar EUV flux was stronger [Ribas et al., 2005, Airapetian and Usmanov, 2016]. The total amount of escaping water content through non-thermal processes can be derived. Another prospect is a comparative study. Since similar studies has recently been made for Mars [Ramstad et al. 2015] and for Earth [Slapak et al. 2017, Schillings et al. 2017], our results can be used for a comparison among the three terrestrial planets. The comparison will provide important implication of the effect of an intrinsic magnetic field, atmospheric content and/or gravity on the escaping oxygen flux.

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COBEX : A small balloon cycling between 40 – 60 km altitudes on Venus to decipher the complex radiative and chemical processes within the clouds and below

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COBEX (Cytherean Oscillating Balloon EXplorer) is a proposed small balloon devoted to the measurement of vertical profiles of p, T, SO_2 density, upwelling and downwelling solar radiation fluxes, and particle densities, sizes and chemical composition in the 40-60 km altitude range in Venus atmosphere. The scientific payload of COBEX is composed of a meteorological package, a multi-wavelength radiometer, a polarizing nephelometer and a tunable diode laser spectrometer. Based on the payload of the *European Venus Explorer (EVE)* (Chassefière et al., 2009), these instruments can fit a mass budget of 3 kg, for a power budget of 7 W. The gondola must also be equipped with a VLBI beacon and a USO for tracking the balloon from Earth and/or from an orbiter. The baseline design for the balloon uses a phase change fluid in order to cycle between 40 and 60 km altitude with a period of typically 6-8 hours (e.g. Nock et al., 1995), but other methods of achieving repeated vertical excursions may be considered. Over a typical travel time of 2 weeks, COBEX may register ≈100 vertical profiles of all measured parameters with a meter-scale vertical resolution in a full range of solar zenith angle conditions.

COBEX can complement a future mission to Venus such as the *VENERA-D* mission, planned to be launched in the latter half of the next decade (Zasova et al., 2017) or coordinated with other missions (.e.g future NASA flagship mission or even the proposed mission to Venus by ISRO) It will be deployed in the atmosphere of Venus by the landing probe of the mission during its descent through the atmosphere. The main questions addressed by COBEX are:

- What is the deposition rate of solar energy within and below the clouds, and what are the nature and effects of particles involved in the radiative budget below Venus main clouds?
- What is the vertical profile of SO_2 throughout the clouds, and how can it be reconciled with the values measured above from orbit, and below by the Vega probes, which cannot be fitted together by existing models?
- What is the vertical profiles of the zonal wind velocity within the clouds and below, and how variable is it with time and solar zenith angle?

Combined with descent probe data, COBEX data will provide a key for unlocking the mysteries of the Venus global cloud cover that is responsible for most of the solar energy deposition in the Venus atmosphere that drives its as yet ill understood super rotation.

A small super-pressure balloon was successfully flown in Venus atmosphere in the 1980s by the Russian-French VEGA mission (Sagdeev et al., 1986). Ten years ago, a low atmosphere Venus balloon has been studied by JAXA. In the same period, CNES performed a preliminary study of a superpressure balloon for the *EVE* mission. Several studies of Venus aerial platforms are underway at JPL. Several projects of Venus orbiters have been studied or are under study in the world: *VOX* in the US, *ENVISION* in Europe, *Indian Venus Orbiter* at ISRO, *Venus Exploration Orbiter* in China. Composition measurements from a descent/landing probe have recently been proposed in the framework of the *VISAGE* and *VICI* mission projects submitted to NASA, but not selected. The time is right to resume the development of a vertically cycling balloon to be able to react rapidly to any new opportunity to explore Venus cloud atmosphere in the next decade.

References

Chassefière et al., *Exp. Astron.* 23, Issue 3, 741-760, 2009
Nock et al., AIAA Lighter-Than-Air Systems Technology Conference, May 15-18, 1995
Sagdeev et al., Pis'ma Astron. Zh. 12, 10-15, 1986
Zasova et al., Report of the Venera-D Join Science Definition Team, 30 January 2017

ENVISION M5 VENUS ORBITER PROPOSAL: STATUS AND OPPORTUNITIES

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Introduction: EnVision [1] is a medium class mission to determine the nature and current state of geological activity on Venus, and its relationship with the atmosphere, to understand how Venus and Earth could have evolved so differently. It is one of three finalists in ESA's M5 selection process and is entering phase 0 / phase A study; final mission selection will be in late 2021 or early 2022. If successful, EnVision will launch by 2032 into a six month cruise to Venus, followed by aerobraking, to achieve a 260 km circular orbit for a 5-year nominal science phase.

Instruments and Science Operations: EnVision hosts three primary instruments:

The S-band Imaging Radar, VenSAR, will:

- Obtain images at a range of spatial resolutions from 30 m regional coverage to 1 m images of selected areas; an improvement of two orders of magnitude on Magellan images;
- Measure topography at 15 m resolution vertically and 60 m spatially from stereo and InSAR data;
- Detect cm-scale change through differential InSAR, to characterize volcanic and tectonic activity, and estimate rates of weathering and surface alteration; and
- Characterize surface mechanical properties and weathering through multi-polar radar data.

The Subsurface Sounder, SRS, will:

- Characterize the vertical structure and stratigraphy of geological units including volcanic flows;
- Determine the depths of weathering and aeolian deposits; and
- Discover as yet unknown structures buried below the surface.

The Venus Emission Mapper, VEM, will:

- Search for temporal variations in surface temperatures and tropospheric concentrations of volcanically emitted gases, indicative of volcanic eruptions; and
- Study surface-atmosphere interactions and weathering by mapping surface emissivity and tropospheric gas abundances.

The Radio Science & Geodesy investigation will:

- Provide gravity and geoid data at a geologically-meaningful scale
- Measure spin rate and spin axis variations to constrain interior structure;
- Profile the atmosphere using radio occultation to understand volatile transport through the clouds.

Secondary payloads: Although the nominal mission going into the Phase 0 / Phase A studies includes only the investigations listed above, it may eventually be possible to enhance the mission with secondary elements. The nominal layout includes one free face which in principle may be used to carry a small additional payload, of 100-200 kg, depending on the characteristics of the launch vehicle (nominally Ariane 6.2). Small Probes, or small orbiters, could be considered.

EnVision could act as both a relay and a data store for other independent missions to Venus, as several Mars orbiters have done, greatly widening the scope for complementary or additional science.

Exhortation: EnVision will produce a huge dataset of geophysical data of a quality similar to that available for Earth and Mars, so will permit investigation across a large range of disciplines. Lab-based and modelling work will also be required to interpret results from the mission. We therefore invite scientists from across planetary, exoplanetary and earth science disiplines to participate in the analysis of the data.

The entire dataset obtained will be made publically available; much of the SAR dataset will be made available in near-real-time to facilitate wide use of the data. We reiterate the opportunity for science experiments and target selection, and encourage researchers to contact the proposers with proposals.

References: [1] Ghail R. C. (2016) *EnVision proposal*, https://arxiv.org/abs/1703.09010.

The Exoplanet Case for Venus

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A fundamental aspect of understanding the limits of habitable environments and detectable signatures is the study of where the boundaries of such environments can occur, and the conditions under which a planet is rendered into a hostile environment. The archetype of such a planet is Earth's sister planet, Venus, and provides a unique opportunity to explore the processes that created a completely uninhabitable world and thus define the conditions that can rule out bio-related signatures. In this talk I will describe the gaps in our knowledge regarding Venus and how this is impacting our ability to model exoplanet atmospheres and interiors. I will outline the premise behind the "Venus Zone" and how testing the conditions of runaway greenhouse is an essential component of understanding the development of habitable conditions. I will present several detected potential Venus analogs including climate simulations that constraint their surface environments. Finally, I will summarize the need for a return mission to Venus and the primary questions that need to be addressed.

VENUS CLIMATE SOUNDER – A LIMB INFRARED RADIOMETER FOR THE MIDDLE ATMOSPHERE OF VENUS. A. Kleinböhl[1], J. T. Schofield[1], T. Navarro[2], [1]Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, [2]University of California, Los Angeles, CA (armin.kleinboehl@jpl.nasa.gov).

Introduction: Despite remarkable progress in understanding the Venusian atmosphere, fundamental questions remain. The key drivers of the atmospheric superrotation are still not identified. The transport of angular momentum is at the core of this issue. Standing waves in the middle atmosphere, recently discovered in thermal imaging from the Akatsuki orbiter [1], offer a new window into likely mechanisms. Major questions include the torque exerted by the atmosphere on the surface due to mountain waves and the altitude at which these waves break. The Venus polar vortex is long-lived but continually evolving, and its development is unpredictable. Its dipole structure has only recently been modeled [2], showing that the thermal tide is a crucial driver of polar atmospheric structure, further complicated by wave interactions. The variability of SO_2 above the cloud layer is another long-standing mystery. UV nadir measurements at 70 km suggest SO_2 fluctuations from <100 to 400 ppb over decadal timescales [3]. Large volcanic eruptions or dynamical changes in the cloud layer may be responsible, but no convincing theory exists to date.

Fig. 1: The MRO/MCS flight instrument during thermal vacuum testing at JPL.

VCS Instrument: The Venus Climate Sounder (VCS) is a passive infrared, limb-sounding, filter radiometer ideally suited to address these questions from a future Venus polar orbiter. VCS builds on flight heritage from the Mars Climate Sounder (MCS, Fig. 1) [4], which has been operating for over 10 years on the Mars Reconnaissance Orbiter (MRO) [5].

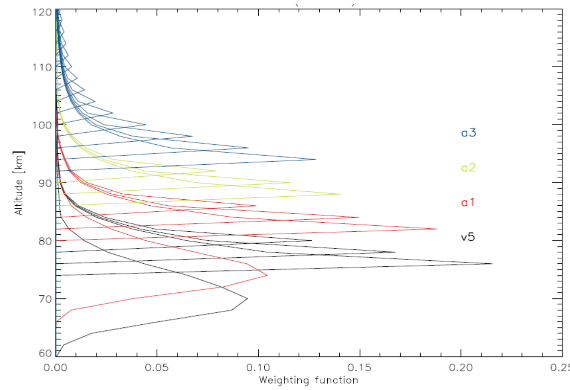

Fig. 2: Vertical response functions of a combined limb/nadir VCS temperature measurement. Colors indicate different channels covering the 15 µm CO_2 band.

VCS would use 13 spectral channels in the IR from 11-45 µm and a vis./near-IR channel to address its measurement objectives. Azimuth and elevation actuators, each with a 270° range, would allow pointing of the telescopes anywhere in the downward hemisphere from a nadir-oriented spacecraft. Each channel would consist of a linear 32 pixel array of uncooled thermopile detectors, measuring a radiance profile when aligned vertically on the limb. The use of limb and nadir geometry from a circular orbit at ~240 km altitude would allow continuous profiling of temperature from near the cloud tops to 120 km altitude (Fig. 2), cloud structure near the cloud tops, water vapor and SO_2 along the orbit track. With a vertical resolution of ~2 km throughout the middle atmosphere, VCS would provide the 3-D view of mountain waves required to characterize their amplitudes and wavelengths. Nadir measurements would allow wide-swath IR imaging particularly relevant for understanding polar vortex dynamics.

Acknowledgments: We thank Hiroki Ando for helpful discussions. Work at the Jet Propulsion Laboratory, California Institute of Technology, is performed under contract with the National Aeronautics and Space Administration.

References: [1] Fukuhara et al. (2017) *Nat. Geosci. 10,* 646-651. [2] Ando et al. (2016*) Nat. Commun. 7,* 10398. [3] Marcq et al. (2013) *Nat. Geosci. 6,* 25-28. [4] McCleese et al. (2007) *JGR 112,* E05S06. [5] Schofield et al. (2018) *COSPAR.*

The First Japan's Planetary Orbiter AKATSUKI's history from 2001 till 2015

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Explorations of Venus led by the USSR and the USA since the 1970s' have revealed that Venus has a thick carbon dioxide atmosphere whose pressure and temperature at the surface reach approximately 90 atm and 700 K, respectively, the latter due to the greenhouse effect. Furthermore, there are no oceans on Venus. It is a mystery why Venus has such different conditions to Earth, which is almost the same size as Venus and a similar distance from the sun. Another mystery is why the Venusian atmosphere rotates so quickly, at almost 100 m/sec at an altitude of 50-60 km at every latitude. Venus itself rotates very slowly westward, at a rate of 243 days. This fast atmospheric flow is called super-rotation, and the rotation time period around Venus is almost 4 Earth days. Our current knowledge of terrestrial meteorology does not explain this circulation process.

Explorations in the 20th century resulted only in a static image of Venus, therefore, Japan proposed a new mission to reveal a more dynamic image of Venusian atmospheric motion in the 2001. This mission is intended to uncover dynamic atmospheric motions at different altitudes and, through detailed analysis, enable us to understand the driving mechanism behind the angular momentum between Venus and its upper atmospheric layer. To achieve these aims, we developed 5 cameras for sequential imaging of different altitude layers. An Ultraviolet Imager (UVI) detects SO_2 and unknown material absorption patterns at 283 nm and 365 nm, respectively, at an altitude of 65 km, and the image sequence reflects cloud motions at this altitude. At almost the same altitude, the cloud top temperature is detected by a long Infrared camera (LIR) at a wavelength of 8-12 μm. Movement of the cloud temperature pattern also provides information on cloud motions. At altitudes of 50 km, 1μm, and 2 μm, infrared cameras (IR1 & IR2) are used to capture images. Observation wavelengths are 0.9, 0.97, and 1.01 μm, and 1.74, 2.02, 2.26, and 2.32 μm, respectively. The LIR detects infrared emission without being affected by the sun, thus it has an equivalent image quality during the day and night. IR1 and IR2 can detect the night-side and day-side of Venus with different exposure times at different wavelengths. Furthermore, hotspots might be detected by IR1, which may represent active volcanoes. Finally, a Lightning and Airglow Camera (LAC) is a high speed photometer with a 30 kH sampling rate used to detect possible lightning in the Venusian atmosphere, which can be an indicator of high speed vertical air flow.

Radio science (RS) is also an important aspect of AKATSUKI observations. When an X band radio transmission from the spacecraft to the ground crosses the Venusian atmosphere, it is refracted and attenuated. This information leads to vertical profiles of temperature, SO2 vapor, and electron density. This is why the RS is called the 6th scientific instrument onboard AKATSUKI. An Ultra-Stable Oscillator (USO) is onboard AKATSUKI for RS purposes, allowing the exiting X band radio emission to be received without interference by the up-link frequency from the ground.

After the Japanese Venus exploration was announced, Europe proposed the Venus Express (VEX) mission. They surveyed the Venusian atmosphere mainly using spectrometers. In other words, the Japan mission planned to survey Venus in a dynamic sense while VEX surveyed Venus from a chemical perspective. These studies are complimentary and both datasets are important for understanding Venus. VEX was operated from 2006 till 2014, and was waiting for the arrival of AKATSUKI, but due to the unfortunate failure of the AKATSUKI Venus orbit insertion in 2010, the opportunity for simultaneous observation was lost.

Using the reaction control systems instead of the broken orbital maneuvering engine, the recovery maneuver was operated on December 7, 2015, and AKATSUKI was finally inserted into an orbit around Venus with a 0.36 million km apoapsis and a 10.5 day orbital period. AKATSUKI currently transmits important scientific data on a daily basis.

Program

No.	Schedule	Name	Organization (abbreviated)	Title	Program No.
	(11:30-12:45)	*Lunch*			
DAY1 (11Tue) PM0	**13:00**	Session00 Opening			
	13:00	**Hironori Iwase**	**The Fujihara Foundation of Science**	**Profile of The Fujihara Foundation of Science**	
	13:20	**Makoto Kobayashi**	**KEK**	**Opening Address**	
DAY1 (11 Tue) PM1	**13:30**	Session 01 Solid body/Geology			
01-1INVITE	**13:30**	**Smrekar Suzanne**	**Jet Propulsion Laboratory/Caltech**	**Venus Interior and Surface Today**	**venus2018-0109**
01-2	13:50	Antoine Billy Rozel	ETH Zurich	Numerical simulations of mantle convection with crust formation, implications for the dynamics of Venus	venus2018-0094
01-3INVITE	**14:05**	**Masaki Ogawa**	**University of Tokyo at Komaba (U-tokyo)**	**A two-stage evolution model of Venus' mantle and its implications for the Earth**	**venus2018-0001**
01-4	14:25	Joseph G O'Rourke	ASU	Signatures of lithospheric flexure and elevated heat flow in stereo topography at coronae on Venus	venus2018-0013
01-5	14:40	Cayman Thomas Unterborn	Arizona State University	Self-Consistent Reference Seismological Models for Determining Venus's Interior Composition	venus2018-0015
01-6	14:55	Anne Davaille	FAST (CNRS, Univ. Paris-Sud)	Plume-induced subduction and ridge dynamics in the expanding Artemis Coronae	venus2018-0105
	(15:25-16:00)	*Coffee*			
Day1 (11 Tue) PM2	**16:00**	Session 02 Evolution (1) Solid Body			
02-1	16:00	Jeffrey Balcerski	NASA GRC	Fault analysis of Venus ridge belts using stereo-derived topography	venus2018-0106
02-2INVITE	**16:15**	**Melinda Darby Dyar**	**Planetary Science Institute Mount Holyoke College**	**Mineral spectroscopy of the surface of Venus**	**venus2018-0050**
02-3INVITE	**16:35**	**Helbert Jorn**	**DLR**	**The Spectroscopy of the surface of Venus –in the laboratory and from orbit**	**venus2018-0059**
02-4	16:55	Martha Gilmore	Wesleyan Univ.	CONTRASTS BETWEEN LOW EMISSIVITY TESSERA AND PLAINS MATERIALS ON VENUS MOUNTAINTOPS	venus2018-0134
02-5	17:10	Erika Kohler	NASA Goddard	Measuring spectral properties of candidate minerals: Applications to the Venus radar anomalies	venus2018-0133
02-6	17:25	Sara Taeko Port	University of Arkansas	The Effects of Venusian Conditions on Galena and Lead	venus2018-0019
	(19:00-21:00)	***Welcome Dinner***			
Day2 (12 Wed) AM1	**8:00**	Session 03 Evolution (2) Climate			
03-1INVITE	**8:00**	**Eric Chassefiere**	**CNRS**	**Recent advances in our understanding of Venus climate evolution and remaining mysteries**	**venus2018-0011**
03-2INVITE	**8:20**	**Cedric Gillmann**	**ULB**	**The early and long term evolution of Venus and its climate.**	**venus2018-0018**
03-3INVITE	**8:40**	**Michael Way**	**NASA/GISS**	**Modeling Venus-like Worlds Through Time: What can they tell us about the the liquid water habitable zone, the evolution of Venus' atmosphere, and conditions amenable to life**	**venus2018-0009**
03-4INVITE	**9:00**	**David Grinspoon**	**Planetary Science Institute**	**The Evolution of Climate and a Possible Biosphere on Venus**	**venus2018-0068**
03-5	9:20	Candace Leah Gray	Apache Point Observatory	Variability of the Venusian and Martian nightside ionosphere after solar storms	venus2018-0051
03-6	9:35	Moa Persson	Swedish Institute of Space Physics (IRF)	Dependence of the H+/O+ flux ratio in the Venusian magnetotail on the solar wind	venus2018-0086
03-7	9:50	Stephen A Ledvina	Space Sciences Lab, UC Berkeley	Simulations of ion flow and momentum transfer in the Venus environment	venus2018-0074
	(10 :05-10:20)	*Coffee*			
Day2 (12 Wed) AM2	**10:20**	Session 04 Aeronomy and Plasma Environment			
04-1INVITE	**10:20**	**Yoshifumi Futaana**	**Swedish Institute of Space Physics**	**Upper atmosphere of Venus and impact from solar wind plasma: What we have learnt from Venus Express?**	**venus2018-0083**
04-2	10:40	Martin Paetzold	RIU-Planetary Research	The Venus Ionosphere as seen by the Akatsuki Radio Science Experiment	venus2018-0098
04-3INVITE	**10:55**	**Amanda Susanne Brecht**	**NASA**	**Understanding the impact of waves on Venus' Upper Atmosphere through General Circulation Model Simulations**	**venus2018-0065**
04-4	11:15	Stephen W Bougher	Michigan	The Impact of Venus Middle Atmosphere Energy Balances upon Dayside Thermosphere Temperature and CO Density Distributions through GCM Model Simulations	venus2018-0062
04-5	11:30	Dmitry Gorinov	IKI	Circulation of Venusian atmosphere at 90-110 km based on apparent motions of the O2 1.27 μm nightglow from VIRTIS-M (Venus Express) data	venus2018-0024
04-6	11:45	Yukihiro Takahashi	HOKKAIDO UNIV.	Search for lightning discharge in Venus with Akatsuki/LAC and Pirka telescope	venus2018-0113
04-7	12:00	Richard A Hart	UCLA EPSS	Statistics of Poynting Flux from Lightning Generated Whistlers at Venus	venus2018-0108
	(12:15-13:40)	*Lunch*			

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No.	Schedule	Name	Organization (abbreviated)	Title	Program No.
Day2 (12 Wed) PM1	**13:40**	Session 05 Clouds and Chemistry			
05-1INVITE	**13:40**	**MARCQ Emmanuel**	**LATMOS / UVSQ**	**Spectroscopy of Venus in the near UV: SO2, clouds and O3**	**venus2018-0034**
05-2	14:00	Takehiko Satoh	ISAS/JAXA	Investigation of high-altitude aerosols of Venus with Akatsuki/IR2 2.02-um images at large phase angles	venus2018-0099
05-3	14:15	Takao Sato	ISAS/JAXA	Mapping of Venus' cloud top altitude from Akatsuki/IR2 dayside images	venus2018-0052
05-4INVITE	**14:30**	**YEON JOO LEE**	**Univ. of Tokyo**	**Intense Decadal Variation of Venus' UV Albedo and its Impacts on the Atmosphere**	**venus2018-0071**
05-5INVITE	**14:50**	**Oksana Shalygina**	**MPS**	**Glory as an effective tool for retrieving the properties of the Venus upper clouds from the VMC/VEx data**	**venus2018-0056**
05-6	15:10	Minori Narita	The University of Tokyo	Correlation of Cloud Morphology at the Venus' Cloud Top between different wavelengths studied with Akatsuki observations	venus2018-0127
05-7	15:25	Michael Radke	Johns Hopkins University	Laboratory investigation of Venus aerosol analogs	venus2018-0067
	(15:40-16:00)			***Coffee***	
Day2 (12 Wed) PM2	**16:00**	Session 06 Poster (1)			
	16:00			Short Presentation	
	16:40			Core Time	
Day3 (13 Thr) AM1	**8:00**	Session 07 Atmoshperic Dynamics(1)			
07-1INVITE	**8:00**	**Sebastien Lebonnois**	**LMD/IPSL, CNRS**	**Investigations below the clouds of Venus with the IPSL Venus GCM**	**venus2018-0044**
07-2INVITE	**8:20**	**Masahiro Takagi**	**Kyoto Sangyo University**	**Numerical modeling of the Venus atmosphere**	**venus2018-0097**
07-3	8:40	Hiroki Kashimura	CPS/Kobe Univ.	Planetary-scale streak structures reproduced in a high-resolution simulation of Venus atmosphere	venus2018-0028
07-4	8:55	Masaru Yamamoto	RIAM, Kyshu Univ.	Venus middle atmospheric simulations using AORI general circulation models	venus2018-0102
07-5	9:10	Aymeric Spiga	LMD / Sorbonne Université	A new mesoscale model for Venus' atmosphere and its application to the bow-shaped structures discovered by Akatsuki	venus2018-0069
07-6	9:25	LEFEVRE Maxence	LMD, Paris	Organization of the convection in the Venusian cloud layer	venus2018-0040
07-7	9:40	Helen F. Parish	UCLA	Investigating the Influence of Wave Variations on Venus' Cloud-level Atmosphere using a Middle Atmosphere Model	venus2018-0010
	(9:55-10:10)			***Coffee***	
Day3 (13 Thr) AM2	**10:10**	Session 08 Poster (2)			
	10:10			Short Presentation	
	10:50			Core Time	
	(12:15-13:40)			***Lunch***	
Day4 (14 Fri) AM1	**8:00**	Session 09 Atmoshperic Dynamics(2)			
09-1INVITE	**8:00**	**Takeshi Horinouchi**	**Hokkaido Univ**	**Venus atmosphere dynamics revealed by cloud tracking using images from Akatsuki**	**venus2018-0030**
09-2INVITE	**8:20**	**Javier Peralta**	**ISAS (JAXA)**	**The complex features and dynamics of the nightside clouds of Venus as revealed by Akatsuki and Venus Express**	**venus2018-0032**
09-3	8:40	Masataka Imai	Hokkaido Univ.	Long-term monitoring of planetary-scale waves in the Venus cloud top layer	venus2018-0029
09-4	8:55	Machado Pedro	I. Astrophysics and Space Sciences	Meridional and Zonal winds at Venus' atmosphere from Cloudtracking, Doppler techniques and comparison with modelling	venus2018-0003
09-5	9:10	Toru Kouyama	AIST	Detection of large stationary gravity waves over six Venusian solar days seen in LIR images	venus2018-0038
09-6	9:25	Eliot Young	SWRI	Nightside cloud tracking: ground-based observations from 2002-2017	venus2018-0123
09-7	9:40	Naomoto Iwagami	none	Cloud morphology and wind measurements by the Akatsuki 1 micro-m camera	venus2018-0021
	(9:55-10:20)			***Coffee***	

revised on Sep 3

No.	Schedule	Name	Organization (abbreviated)	Title	Program No.
Day4 (14 Fri) AM2	**10:20**	Session 10 Atmoshperic Dynamics(3)			
10-1	10:20	Makoto Taguchi	Rikkyo University	Morphology of thermal structures at the Venusian cloud-tops	venus2018-0075
10-2	10:35	Thomas Navarro	UCLA	Interactions between the topography and the atmosphere on Venus	venus2018-0035
10-3	10:50	Tetsuya Fukuhara	Rikkyo Univ.	Local time variation of the cloud-top temperature obtained by close-up observations of LIR	venus2018-0077
10-4INVITE	**11:05**	**Jonathan L. Mitchell**	**UCLA**	**Planetary ageostrophic instability leads to superrotation**	**venus2018-0090**
10-5INVITE	**11:25**	**Alexander Rodin**	**MIPT**	**Gas dynamics simulations of the general circulation of Venus atmosphere**	**venus2018-0142**
10-6	11:45	Franklin Mills	ANU and SSI	Simulations of Vertical Profiles of Sulfur Oxides in Venus' Mesosphere	venus2018-0058
10-7	12:00	Takeshi Kuroda	NICT/Tohoku Uni.	Maintenances of Venusian Sulfuric Acid Clouds and SO2 Abundances due to Chemistry and Dynamics Simulated by a General Circulation Model	venus2018-0020
	(12:15-13:40)			***Lunch***	
Day4 (14 Fri) PM1	**13:40**	Session 11 Atmoshperic Structure			
11-1INVITE	**13:40**	**George L. Hashimoto**	**Okayama University**	**Climate control on Venus: Connections among clouds, UV absorber, surface chemical reaction, and atmospheric circulation**	**venus2018-0096**
11-2	14:00	Alexander B. Akins	Georgia Institute of Technology	Understanding the Millimeter Wavelength Continuum Emission from Venus	venus2018-0004
11-3INVITE	**14:15**	**Takeshi Imamura**	**Univ Tokyo**	**Local time-dependent structures in and below Venusian clouds revealed by Akatsuki radio occultation experiments**	**venus2018-0122**
11-4	14:35	Hiroki Andou	Kyoto Sangyo University	Mean thermal structure in the Venusian lower atmosphere investigated by Venus Express and Akatsuki radio occultation measurements	venus2018-0007
11-5	14:50	Gabriella Gilli	IA, Portugal	The puzzling transition region of Venus atmosphere studied by a ground-to-thermosphere 3D model	venus2018-0025
11-6	15:05	Carver Jay Bierson	UC Santa Cruz	A fully coupled photochemical-condensation model of the Venus atmosphere from ground to 110 km	venus2018-0066
11-7	15:20	Kandis-Lea Jessup	SwRI Boulder (Akatsuki NASA PS)	On Venus' Cloud Top Chemistry, Convective Activity and Topography: A Perspective from HST	venus2018-0070
11-8	15:35	Ralph Lorenz	APL	The Dust Cycle on Venus	venus2018-0060
	(15:50-16:20)			***Coffee***	
Day4 (14 Fri) PM2	**16:20**	Session 12 Future Missions			
12-1	16:20	Jonathan Grandidier	JPL	Solar Spectrum and Intensity Analysis Under Venus Atmosphere Conditions for Photovoltaics Operation	venus2018-0006
12-2	16:35	Attila Komjathy	NASA JPL	Venus Airglow Measurements and Orbiter for Seismicity (VAMOS): A SmallSat Mission Concept Study	venus2018-0046
12-3	16:50	James Alfred Cutts	Jet Propulsion Laboratory	Exploration of Venus with Aerial Platforms	venus2018-0049
12-4	17:05	Grimm Robert	SwRI	High-Altitude Sounding of the Interior of Venus: Stratospheric Balloon Test	venus2018-0107
12-5	17:20	D'Incecco Piero	Arctic Planetary Science Institute (APSI)	The geologic study of Imdr Regio as an opportunity to observe active volcanism on Venus in the perspective of future missions	venus2018-0017
12-6	17:35	Tibor Kremic	NASA	Preparing for Venus Surface Exploration	venus2018-0033
12-7	17:50	Liudmila V Zasova	IKI RAS	DEVELOPMENT OF THE VENERA-D MISSION CONCEPT, FROM SCIENCE OBJECTIVES TO MISSION ARCITECTURE.	venus2018-0111
	(19:30-21:30)			***Banquet***	
Day2 (12 Wed) PM2(Odd #) Day3 (13 Thr) AM2(Even#)			Session 6 and 8	Poster	
P01		Gilles BERGER	IRAP, Toulouse	Experimental investigation of wet atmosphere-surface interaction at the conditions of Venus surface: an example for early terrestrial planets	venus2018-0089
P02		Joseph G O'Rourke	ASU	Prospects for an ancient dynamo and modern crustal remanent magnetism on Venus	venus2018-0014
P03		Siddharth Krishnamoorthy	NASA Jet Propulsion Laboratory	PROSPECTS FOR THE INVESTIGATION OF VENUS' INTERIOR USING INFRASOUND	venus2018-0063
P04		Noam R Izenberg	JHU/APPL	Reinvestigation of Venusian Splotches with Magellan and Arecibo Radar Data	venus2018-0064
P05		Eugene Shalygin	MPS	Are the steep-sided domes produced of non-basaltic lava?	venus2018-0057
P06		Saman Karimi	Johns Hopkins University	Revisiting Crater Relaxation and its Implication on Venus	venus2018-0078

No.	Schedule	Name	Organization (abbreviated)	Title	Program No.
P07		Kazuo Mimura	Tokai University	On the superrotation which is obtained in rotating water tank experiment	cancelled
P08		Yoshiyuki O. Takahashi	Kobe University	Development of a radiative transfer model for a Venus general circulation model	venus2018-0093
P09		Koichiro Sugiyama	Matsue College of Technology	A Three-dimensional Numerical Simulation of Venus' Cloud-level Convection	venus2018-0136
P10		Sebastien Lebonnois	LMD/IPSL, CNRS	An experiment to investigate Venus's deep atmosphere	venus2018-0043
P11		Sebastien Lebonnois	LMD/IPSL, CNRS	Composition and clouds, some insights and questions from the coupled IPSL Venus GCM	venus2018-0045
P12		Sanjay Shridhar Limaye	ISAS / UW-Madison	Cloud Cover of Venus	venus2018-0026
P13		Seiko Takagi	Hokkaido University	The global variation of Venus' clouds obtained from IR1 camera onboard AKATSUK	venus2018-0120
P14		Daria Evdokimova	IKI / LATMOS	Cloud variations and water vapor abundance near the Venus surface from the night-side windows observations by the SPICAV IR/Venus-Express.	venus2018-0143
P15		Yusuke Nara	Univ. Tokyo	Formation of planetary-scale ultraviolet contrast at the Venus' cloud top by horizontal material transport induced by planetary-scale waves and the mean circulation: analysis of VEx/VMC images	venus2018-0117
P16		Kevin McGouldrick	LASP / U. Colorado	Capricious Cytherean Clouds: The Long and the Short of It	venus2018-0114
P17		Naoya Kajiwara	the University of Tokyo	Periodic analysis of the limb darkening in Venus' thermal images taken by Akatsuki LIR	venus2018-0121
P18		Choon Wei Vun	SOKENDAI	Venus IR2 Image Reduction (RS, RD and RDS) and its Scientific Outcomes	venus2018-0061
P19		YEON JOO LEE	Univ. of Tokyo	Venus glory: A key to understand cloud aerosols' properties and absorptions using images	venus2018-0072
P20		YEON JOO LEE	Univ. of Tokyo	Akastuki Team's Supporting System for Coordinated Venus Observations	venus2018-0125
P21		Mikhail Luginin	Space Research Institute (IKI) of the Russian Academy of Sciences	Retrieval of upper haze aerosol properties from SPICAV-UV and -IR data	venus2018-0141
P22		Denis Belyaev	IKI RAS	Joint SPICAV/VIRTIS observations of the UV albedo of Venus	venus2018-0084
P23		Takehiko Akiba	Tohoku University	Radiative balances, horizontal distributions of clouds and large-scale effects of eddies revealed by a Venus General Circulation Model with radiatively-active clouds	venus2018-0119
P24		Norihiko Sugimoto	KEIO University	The Venus AFES LETKF Data Assimilation System (VALEDAS)	venus2018-0023
P25		Ryan Matthew McCabe	Hampton U.	Observational Analysis of Venusian Atmospheric Equatorial Waves and Superrotation	venus2018-0101
P26		Ehouarn Millour	LMD	Towards a (GCM-based) Venus Climate Database	venus2018-0079
P27		Takeshi Horinouchi	Hokkaido Univ	A novel cloud tracking method and results from Akatsuki	venus2018-0031
P28		Toru Kouyama	AIST	Long-term variation of super rotation seen in Akatsuki observations	venus2018-0039
P29		Khatuntsev Igor	Space Research Institute of the Russian Academy of Sciences (IKI)	Winds in the middle cloud deck from 965 and 1010 nm imaging by the VMC onboard Venus Express	venus2018-0016
P30		Adhithiyan Neduncheran	UPES, India	Cloud movements in the Venusian Southern Hemisphere	venus2018-0047
P31		Keishiro Muto	Univ. Tokyo	An improved cloud tracking method applied to Akatsuki UVI images to study atmospheric circulation in the Venusian polar region	venus2018-0126
P32		Hideo Sagawa	Kyoto Sangyo Univ.	Doppler-wind observations of Venus mesospheric circulation: Revisiting previous dataset and comparing with new GCM experiments	venus2018-0137
P33		Thomas Widemann	Paris Obs.	Simultaneous wind measurements with thermal and microphysical properties investigations at cloud tops during Akatsuki's July 29, 2018 pericenter passage : a joint CFHT – Akatsuki campaign	venus2018-0124
P34		Ruben Gonçalves	IA-FCUL	Akatsuki (space-based cloud-tracking) and TNG/HARPS-N (ground-based Doppler velocimetry) coordinated wind measurements of cloud top Venus' atmosphere	venus2018-0005
P35		Liudmila V Zasova	IKI RAS	TRACES OF SURFACE TOPOGRAPHY IN VENUS ATMOSPHERE FROM THERMAL INFRARED SPECTROMETRY	venus2018-0132
P36		Marina Patsaeva	Space Research Institute of the Russian Academy of Sciences (IKI)	Influence of the local time and Aphrodite Terra topography on the cloud top circulation from VMC/Venus Express imaging	venus2018-0008
P37		Takeru Yamada	Rikkyo Univ.	Vertical propagation of the large stationary gravity waves in the Venus atmosphere	venus2018-0073
P38		Gourav Mahapatra	TU Delft	Observing upper atmospheric gravity waves on Venus using polarimetry	venus2018-0103
P39		Yuki FUTAMURA	Hokkaido Univ.	Polarimetric observation of ice crystals in Venus cloud Pirka telescope	venus2018-0129
P40		Masataka Imai	Hokkaido Univ.	Cosmic rays detected by LAC on board Akatsuki	venus2018-0118
P41		Christopher Dennis Parkinson	University of Michigan	Photochemical Control of the Distribution of Venusian Water and	venus2018-0054
P42		Christopher Dennis Parkinson	University of Michigan	Modeling of Observations of the OH Nightglow in the Venusian Mesosphere	venus2018-0053
P43		Yusuke Nara	Univ. Tokyo	Interaction between the thermosphere and the cloud-level atmosphere of Venus studied with simultaneous observations by Hisaki and Akatsuki	venus2018-0115
P44		KATSUYUKI NOGUCHI	NWU	Radio scintillation during Venusian atmospheric occultations by Akatsuki	venus2018-0022
P45		Kosuke Takami	Tohoku University	Coordinated observations using the ground-based IR heterodyne spectrometer and Akatsuki/RS in 2018	venus2018-0100
P46		Bocanegra Bahamon M Tatiana	TUDelft/JIVE	Venus Express radio occultations observed with the Planetary Radio Interferometry and Doppler Experiment (PRIDE)	venus2018-0138
P47		Silvia A. Tellmann	RIU Planetary Research Cologne	Eight years of VEX-VeRa radio sounding of the Venus atmosphere	venus2018-0080
P48		Martin Paetzold	RIU-Planetary Research	small-scale disturbances in the lower dayside ionosphere of Venus	venus2018-0130
P49		Martin Paetzold	RIU-Planetary Research	Eight years of VEX-VeRa radio sounding of the Venus ionosphere	venus2018-0131
P50		Janusz Oschlisniok	Univ. Cologne, RIU Planetary Research, Germany	Sulfuric acid vapor in the atmosphere of Venus as observed by the Venus Express Raio Science Experiment VeRa	venus2018-0088

No.	Schedule	Name	Organization (abbreviated)	Title	Program No.
P51		Gabriella Stenberg Wieser	Swedish Institute of Space Physics (IRF)	Ion temperature anisotropies in the Venus plasma environment at solar minimum	venus2018-0081
P52		Moa Persson	Swedish Institute of Space Physics (IRF)	Venus' atmospheric ion escape rate dependence on upstream solar wind conditions	venus2018-0087
P53		Chuanfei Dong	Princeton University	Solar wind interaction with Venus: From the planetary interior to interplanetary space	venus2018-0092
P54		Eric Chassefiere	CNRS	COBEX : A small balloon cycling between 40 – 60 km altitudes on Venus to decipher the complex radiative and chemical processes within the clouds and below	venus2018-0012
P55		Eric Chassefiere	CNRS	MPVIEW : A multi-satellite mapping system to fully monitor and characterize waves in Venus' atmosphere	venus2018-0042
P56		R.C. Gahil (Colin F Wilson)	Oxford University	ENVISION M5 VENUS ORBITER PROPOSAL: STATUS AND OPPORTUNITIES	venus2018-0144
P57		Martha Gilmore	Wesleyan Univ.	THIRTY DAYS ON VENUS: CHEMICAL AND ELECTRICAL CHANGES MINERALS EXPOSED TO THE GLENN EXTREME ENVIRONMENT RIG (GEER).	venus2018-0135
P58		Stephen Kane	University of California, Riverside	The Exoplanet Case for Venus	venus2018-0027
P59		Smrekar Suzanne	Jet Propulsion Laboratory/Caltech	VERITAS (VENUS EMISSIVITY, RADIO SCIENCE, INSAR, TOPOGRAPHY AND SPECTROSCOPY): A PROPOSED DISCOVERY MISSION	venus2018-0145
P60		Armin Kleinboehl	Jet Propulsion Laboratory	Venus Climate Sounder – A Limb Infrared Radiometer for the Middle Atmosphere of Venus	venus2018-0037
P61		Adhithiyan Neduncheran	UPES, India	Remote Sensing Studies on Venus	venus2018-0048
P62		Masato Nakamura	ISAS/JAXA	The First Japan's Planetary Orbiter AKATSUKI's history from 2001 till 2015	venus2018-0091

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