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Analyses of spectroscopic and atmospheric parameter influences on radiative heating and cooling rates in the middle and lower atmosphere of Venus

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Abstract

Radiative fluxes and temperature change rates in the middle and lower atmosphere of Venus (0-100 km) are calculated over the broad spectral range 0.125-1000 µm applying a radiative transfer model. Responses of these quantities to both spectroscopic model parameter changes and atmospheric parameter variations are examined in great detail. A new model for the unknown UV absorber is proposed. The calculated radiative cooling/heating rates are very reliable at altitudes below 95/85 km at fixed atmospheric conditions with maximum uncertainties of about 0.25 K/day. Heating uncertainties may reach 3-5 K/day at 100 km. Cooling rates strongly respond to variations of atmospheric thermal structure, while heating rates are less sensitive. Except for episodic SO_2 boosts, the influence of mesospheric minor gas abundance variations is rather small, but variations of cloud mode parameters may significantly alter radiative temperature change rates up to 50% in Venus' lower mesosphere and upper troposphere.

1. Radiative transfer model

A sophisticated radiative transfer model (RTM) is applied to calculate radiance and flux spectra in dependence on spectroscopic and atmospheric parameters. The RTM considers absorption, emission, and multiple scattering by gaseous and particulate constituents [1, 4] at infrared (0.7-1000 µm), visible (0.4-0.7 µm), and ultraviolet (0.1-0.4 µm) wavelengths. Look-up tables of quasi-monochromatic absorption cross-sections of gaseous constituents in the infrared and visible spectral ranges are calculated on the basis of a line-by-line procedure for a variety of temperature and pressure values being representative for Venus' atmosphere at altitude levels between the surface and 140 km. These tables are generated for different sets of spectroscopic parameters including very fine spectral sampling steps down to 0.0001 cm^{-1}, different spectral line catalogues, and variations of line profiles with respect to line cut and sub-Lorentz structure. Laboratory data on UV absorption cross-sections of CO_2, H_2O, OCS, and HCl are considered. Mie scattering theory is applied to derive wavelength-dependent micro-physical parameters of Venus' cloud modes.

Apart from spectroscopic studies, present investigations are devoted to detailed analyses of individual atmospheric parameter influences. This ensures a better understanding of possible responses of calculated output quantities with respect to the atmospheric energy balance. Thus, initial atmospheric standard models are selected here rather than utilizing parameter fields that have been recently retrieved from VIRTIS-M-IR data [1-3]. Both initial and retrieved features encompass altitude profiles of temperature, minor gas abundances, and cloud mode particle densities as well as cloud mode chemical composition.

Consideration of an additional atmospheric absorber is required to fit observations of Venus' spectral Bond albedo shortward of 0.8 µm down to 0.32 µm. A new model for the unknown UV absorber being located at altitudes between 57 and 70 km is developed [4]. It is not directly linked to cloud particle modes 1 or 2, and thus, permits an investigation of the absorbers' radiative effects regardless of its chemical composition.

2. Results

On global average, half of the solar flux received at the top of atmosphere (TOA, 667 Wm^{-2}) is absorbed by CO_2 and cloud mode 1 and 2 particles at altitudes above 74 km. The sum of direct and diffuse downward solar fluxes attains the 50% level of TOA flux at 55 km. About 5% of solar TOA flux reaches the surface. The globally averaged Bond albedo of Venus results as 0.763 in accordance with previous findings. The global average of solar net flux deposited on the planet is 158.1 Wm^{-2}, and the corresponding outgoing thermal net flux is 159.7 Wm^{-2} for the used initial atmospheric standard models. Exact TOA global radiative equilibrium is achieved by moderate adjustments of cloud mode and UV absorber abundances.

The use of absorption cross-section databases at a spectral point distance of 0.01 cm^{-1} is shown to be sufficiently accurate over the entire spectral range. Based on an attentive separation of ranges that are dominated by strong or weak gaseous absorption bands, an optimum point distance grid is defined that considerably accelerates the time expensive monochromatic flux calculations without introducing significant accuracy losses (< 0.1 K/day below 85 km, <1.5 K/day at 100 km). Largest uncertainties of temperature change rates may result when different spectral line catalogues are used. At 100 km, they may reach 3.0 (0.3) K/day for heating (cooling), while the deviations with respect to net heating would partly compensate between 70 and 90 km. The use of different sub-Lorentz profiles and line cut conditions does not significantly alter cooling and heating results above 50 km, but for accurate thermal flux and cooling rate calculations in the region of the cloud base (48 km) the use of a line cut condition of at least 250 cm^{-1} is recommended. It is concluded that the calculated cooling and heating rates at fixed atmospheric conditions are very reliable at altitudes below 85 km with maximum uncertainties of about 0.25 K/day. Cooling uncertainties do not increase between 85 and 95 km, but heating uncertainties may reach 3-5 K/day at 100 km. The use of equivalent Planck radiation as solar insolation source should be avoided, since it seriously overestimates solar heating shortward of 0.4 µm.

There is a very strong response of cooling rates to variations of atmospheric thermal structure, while heating rates are less sensitive. Except for observed episodic strong SO_2 abundance boosts, the overall response of the radiative energy balance on minor gas abundance variations is rather small in the mesosphere, but such variations (especially H_2O and SO_2) may become more important near the cloud base. The influence of mode 1 cloud particles is found to be comparatively small (<0.12 K/day at 70 km when halving the column abundance). Changes of mode 2, 2', and 3 parameters (cloud top and base altitudes, column abundances, upper scale heights) may significantly alter radiative temperature change rates up to 50% in Venus' lower mesosphere and upper troposphere. The new nominal model for the unknown UV absorber provides 50% more heating at 68 km compared with a neglect of this opacity source.

Preliminary results on net radiative forcing in the atmosphere of Venus as functions of latitude and altitude (neglecting cloud parameter changes with latitude at this stage) indicate a broad net cooling region between 70 and 80 km with a strong increase of cooling toward the poles. A net rate gradient is also observed at 65 km where heating prevails at low latitudes. At altitudes above 80 km, net heating dominates the low and mid latitudes, while net cooling prevails at high latitudes leading to a dominant global average net heating. The observed thermal structure in the Venus mesosphere can only be maintained by dynamical processes, therefore.

3. Outlook

Upcoming studies will consider improved models of middle and lower atmospheric parameters of Venus that have been retrieved from VIRTIS-M-IR data [1-3] with respect to latitude and local time dependent thermal structure and meridional variations of cloud features and minor gas distributions. Based on the present results, variations of cloud mode abundances and cloud top and base altitudes are expected to considerably alter the results on atmospheric radiative energy balance of Venus.

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EPSC Abstracts
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A mysterious structure of Venusian upper polar atmosphere reproduced by a general circulation model

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Abstract

The polar cold collar, a cold band zonally surrounding the warm polar vortex at ~60˚ latitude, is a unique feature observed at the ~65 km level in the Venus atmosphere. As this structure has been observed in numerous previous observations, the cold collar and warm polar vortex are robust features in the Venus upper atmosphere [1]. We performed numerical simulations of Venus atmospheric circulation using a general circulation model (GCM) named AFES for Venus, and observed that these features are reproduced in close agreement with the observations. The cold collar and warm polar vortex might be contributed to residual mean meridional circulation closely related to thermal tides. The present results suggest that the thermal tides might be crucial for the structure of the Venus upper polar atmosphere at and above cloud levels.

1. Introduction

Venus atmospheric dynamics has been studied numerically using GCMs. However, there were no numerical studies which succeeded in reproducing a unique structure of the Venus polar atmosphere in realistic model settings.

Thermal tides are planetary scale waves excited by the solar heating. In the Venus atmosphere, they are strongly excited at the cloud levels because a large part of the solar flux is absorbed there [2]. However, their effects on the atmospheric structure in the polar region have not yet been examined. In this study, we investigate the structure of the Venus upper polar atmosphere using a GCM named AFES for Venus. To examine the dynamical effects of thermal tides, we perform two numerical experiments with observation-based distributions of solar heating: one with the diurnal components (Case A) and one without them (Case B). The thermal tides are excited only in Case A. See Sugimoto et al. (2014) [3] for the details of the model settings.

2. Results and Discussion

Fig. 1 shows the time evolution of the horizontal temperature distribution at ~68 km obtained in Case A. The cold collar surrounds the warmer polar region at ~60°N. The maximum temperature difference between 60°N and the pole is ~20 K. As shown in Fig. 1, zonal components with wavenumbers of zero and one are predominant in the temperature distribution in the cold collar.

Figs. 2a and 2b show latitude–height distributions of zonal- and temporal-mean zonal wind and temperature above the cloud top level averaged over two Venusian solar days (~234 Earth days) obtained in Cases A and B. The axis of the midlatitude jet in Case A is located at a lower latitude and altitude than in Case B. This might be due to the momentum transport by thermal tides. In Case A, the temperature decreases with latitude in association with the positive vertical shear of the mean zonal wind in the equator-side of 60°N with height below 70 km; whereas the temperature increase with latitude in the pole-side of 70˚N with height above 67 km. A remarkable cold collar is observed at 67–70 km levels at 60°–70° latitudes along with the polar warm region indicated by red color near the north pole. In Case B, on the other hand, temperature monotonically decreases with latitude in the region below 75 km height. The polar warm region shrinks and shifts to a region above 76 km indicated by light blue color near the north pole. The cold collar also appears in Case B at latitudes of 60°–70° at ~80 km levels; however, the temperature difference between the cold collar and polar region is less than 5 K, which is considerably smaller than that in Case A, and not clearly shown in Fig. 2b. Figs. 2c and 2d show temporally averaged residual mean meridional circulation by arrows and mass stream function by contours, in Cases A and B, respectively. In Case A, the residual mean meridional circulation above the cloud-top level (~70 km) reaches the polar region and remarkable downward motion occurs, which warms the atmosphere through adiabatic heating and forms the polar warm region. Also in Case B, the downward motion of the residual mean meridional circulation is observed in the polar region. However, it is three times slower than that in Case A, and the adiabatic heating rate associated with the downward flow in the polar region in Case B is much lower than that in Case A.

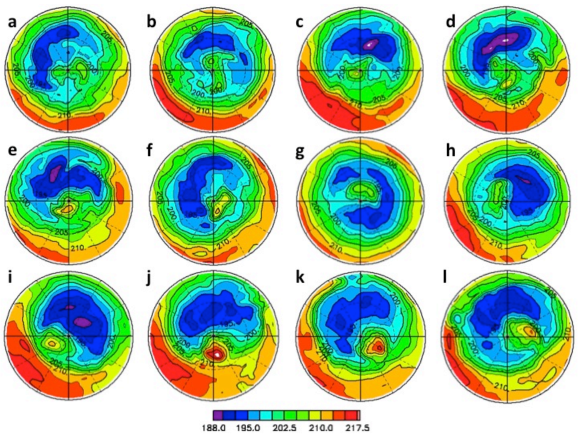

Figure 1: Time evolution of temperatures (K) in the polar plot at the altitude of ~68 km (the pressure level of 4×10^3 Pa) in Case A. The time interval of respective figures is one day.

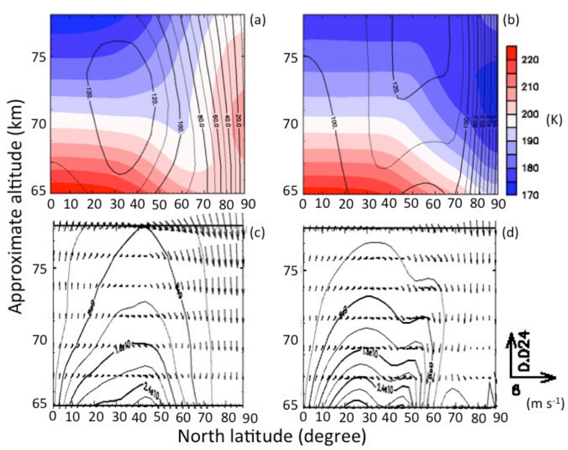

Figure 2: (Top) Meridional cross sections of the zonal- and temporal-mean zonal wind (solid line) and (colour shade); and (Bottom) the residual mean meridional circulation (vector) and mass stream function (contour). Left (a and c) and right (b and d) figures are for Cases A and B, respectively.

3. Summary

Our simulations elucidate the importance of thermal tides for the Venus atmospheric circulation around the cloud-top level (~70 km). The cold collar and polar warm region can be explained by the downward motion of the residual mean meridional circulation, which is closely related to thermal tides. This is qualitatively similar to Earth's sudden stratospheric warming, which is related to the meridional circulation induced by upward propagating Rossby waves [4]. The present work is helpful for interpreting numerous observations and features of the Venus upper atmosphere.

Acknowledgements

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EPSC Abstracts
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SIGNS OF FLORA AND FAUNA ON VENUS AND THEIR CHARACTERIZATION

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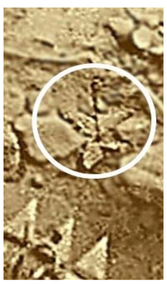
For thousands of years, humanity has wondered whether there is life outside the Earth. Habitability of planets is a fundamental question of astrophysics. Some of exoplanets possess physical conditions close to those of Venus. Therefore, the planet Venus, with its dense and hot (735 K) oxygen-free atmosphere of CO_2, having a high pressure of 9.2 MPa at the surface, can be a natural laboratory for this kind of studies. The only existing data on the planet's surface are still the results obtained by the Soviet VENERA landers.



The TV experiments of Venera-9 and 10 (October, 1975) and Venera-13 and 14 (March, 1982) delivered 41 panoramas of Venus surface (or their fragments). The experiments were of extreme technical complexity. There have not been any similar missions to Venus in the subsequent 40 and 33 years. In the absence of new landing missions to Venus, the VENERA panoramas have been re-processed by modern means. The results of these missions are studied anew. A dozen of relatively large objects, from a decimeter to half a meter in size, with an unusual morphology have been found which moved very slowly or changed slightly their shape. Certain unusual findings that have a structure similar to the Earth' fauna and flora were found in different areas of the planet. There are more then 30 papers of L.Ksanfomality on the topic published in 2012-2014.

Venusian hypothetical 'Footstalk'
Lizard-like "amisada'**.**

Due to the availability of up to eight duplicates of the images obtained and their low level of masking noise, the VENERA archive panoramas permit identifying and exploring some types of hypothetical life forms of Venus. Analysis of treated once again VENERA panoramic images revealed objects that might indicate the presence of about 12 hypothetical forms of Venusian flora and fauna. Among them is 'amisada' that stands out with its unusual lizard shape against the stone plates surrounding it.

Literature

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EPSC Abstracts
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Geographic distribution of zonal wind and UV albedo at cloud top level from VMC camera on Venus Express: Influence of Venus topography through stationary gravity waves vertical propagation.

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Abstract

Based on the analysis of UV images (at 365 nm) of Venus cloud top collected with VMC camera on board Venus Express [4,5], it is found that the zonal wind speed south of the equator (from 5°S to 15°s) shows a conspicuous variation with geographic longitude of Venus, correlated with underlying relief of Aphrodite Terra. We interpret this pattern as the result of stationary gravity waves produced at ground level by the up lift of air when the horizontal wind encounters a mountain slope. The cloud albedo map at 365 nm varies also in longitude and latitude, perhaps the result of increased vertical mixing associated to wave breaking, and decreased abundance of the UV absorber which makes the contrast in images.

1. Introduction

The comparison of two consecutive UV images of the UV-markings cloud pattern collected by VMC camera on board VEX allowed to derive a large number of wind measurements at altitude 67±2 km from tracking of cloud features [1] in the period 2006-2012. Both manual (45,600) and digital (391,600) individual wind measurements over 127 orbits were analyzed, showing various patterns with latitude and local time. A new longitude-latitude geographic map of the zonal wind shows a conspicuous region of strongly decreased zonal wind, a remarkable feature that was unknown up to now (fig.1 top). While the average zonal wind near equator (from 5°S to 15°s) is -100.9 m/s in the longitude range -160 to -30°, it reaches -83.4 m/s in the range 60-100°, a difference of 17.5 m/s.

When compared to the altimetry map of Venus (fig.1 bottom), it is found that the zonal wind pattern is well correlated with the underlying relief in the region of Aphrodite Terra, with a downstream shift of about 30° (~3,200 km).

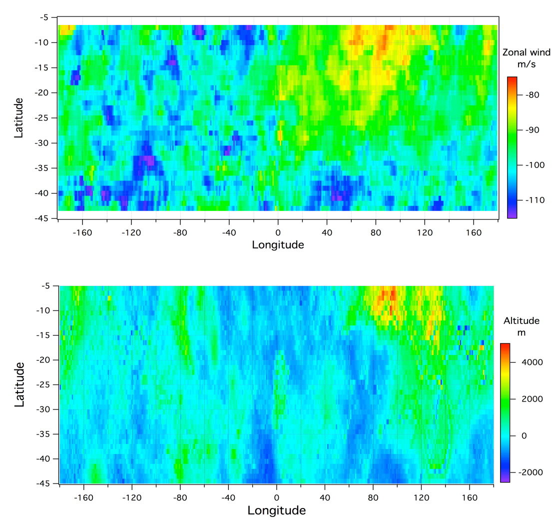

Figure 1 **Top**: Map of the zonal wind speed is in m/s (color coded). There is a region of strong minimum (in absolute value) which is located ~30° downstream of the high lands. **Bottom**: Partial topographic map

of Venus. Altitude is color coded. The latitude coverage of the map is limited from 5° S to 45° S to match the map of zonal wind. The zonal wind is oriented from right to left, from East to West, toward decreasing longitudes.

2. Influence of stationary gravity waves.

We interpret this pattern as the result of stationary gravity waves produced at ground level by the up lift of air when the horizontal wind encounters a mountain slope (fig.2). These waves can propagate up to cloud top level, break there and transfer their momentum to the zonal flow. A similar phenomenon is known to operate on Earth with an influence on mesospheric winds [3]. The LMD-GCM for Venus was run with or without topography, with and without a parameterization of gravity waves do not display such an observed change of velocity near equator.

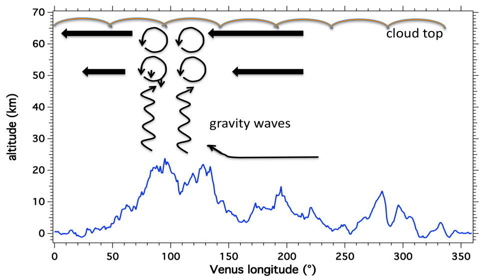

Figure 2. Sketch of gravity waves generated by interaction of the zonal wind on the mountains (blue line), propagating upward, breaking in the altitude region 50-60 km and decelerating the zonal wind at this altitude and higher. The blue line represents the actual average altitude of the mountains (5°S to 15°S), multiplied by a factor ~6.

3. UV albedo mapping.

The cloud albedo map at 365 nm varies also in longitude and latitude. On figure 3 is displayed a geographic map of the UV albedo at 365 nm measured by VMC. It is an average of 1442 images obtained over 7.5 years from May 2006 to September 2013. While the albedo poleward of 40°S is pretty uniform and higher than near the equator, a well known fact [2], there are totally unexpected structures at other places nearer the equator, both in longitude and latitude. We speculate that it might be the result of increased vertical mixing associated to wave breaking, and decreased abundance of the UV absorber which makes the contrast in images.

The impact of these new findings about velocity and albedo on current super rotation theories remains to be assessed.

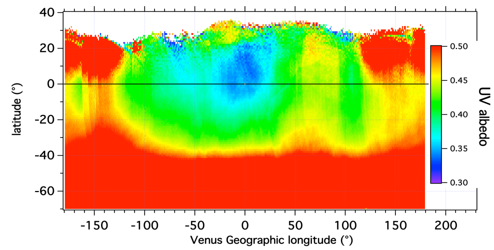

Figure 3. Venus geographic map of the UV albedo. The albedo A is derived from the VMC measured UV radiance (345 to 385 nm) assuming a Lambert behavior. A= π radiance/(solar flux cos(sza)), sza=solar zenith angle. A was averaged in each 1x1° bin of longitude-latitude (only sza<70°). The number of points per bin ranges from ~1000 to 5000.

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EPSC Abstracts
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A compilation of all CO observations performed by SOIR during the Venus Express mission

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Abstract

The SOIR instrument on board the ESA Venus Express spacecraft has been operational during the complete duration of the mission, from April 2006 up to November 2014. Spectra are recorded in the IR spectral region (2.2 -4.3 µm) using the solar occultation geometry and give access to a vast number of ro-vibrational lines and bands of several key species of the atmosphere of Venus. Here we present the complete set of vertical profiles of carbon monoxide (CO) densities and volume mixing ratios (vmr) obtained during the mission. These profiles are spanning the 65-150 km altitude range. We discuss the variability which is observed on short term, but also the long term trend as well as variation of CO with solar local time (LST) and latitude.

1. Introduction

The SOIR (Solar Occultation in the IR) instrument has been designed to measure spectra of the Venus atmosphere in the IR region (2.2 – 4.3 µm) using the solar occultation technique [1]. This method derives unique information on the vertical composition and structure of the mesosphere and lower thermosphere. The SOIR instrument is unique in terms of spectral coverage and spectral resolution (0.15 cm^{-1}), and is ideally designed to probe the Venus atmosphere, above the cloud deck, for CO_2 as well as trace gases. CO is particularly well covered since the (2-0) band strongly absorbs in the 3900-4400 cm^{-1} range, which is well inside the sensitivity range of the SOIR instrument.

2. Data sets and retrieval technique

The retrieval method has already been described in details elsewhere for CO_2 and temperature [2] and specifically for trace gases [5]. The method determines the number densities, temperature and aerosol extinction profiles using an iterative procedure.

The primary results deduced from the analysis of SOIR spectra are densities. Conversion to volume mixing ratio (vmr) requires the knowledge of the total density, or that of CO_2, if a CO_2 vmr is assumed. Two cases are encountered: either the CO_2 density is retrieved simultaneously from one of the 4 orders dedicated to its detection and is directly used to obtain the vmr, or no information on CO_2 is available from the observation itself. In that case, the CO_2 density will be derived from the VAST model, which has been described in detail in [3] and updated in [4]. In both cases, an assumption is made on the CO_2 mixing ratio, whose values are taken from the VIRA model.

All SOIR observations are performed at the terminator, either on the day side (LST 6 am) or night side (LST 6 pm) and cover both hemispheres from 90S to 90N latitudes. The instrument probes the mesosphere (70 to 95 km) and the lower thermosphere (above 95 km). CO has been observed regularly during the Venus Express mission. Table 1 gives the number of observations for the different latitudinal bins considered in this study (0°-30°, 30°-60°, 60°-70°, 70°-80°, 80°-90°). Day/night difference have been considered, for both North and South hemispheres. The equatorial and mid-latitude regions considered in this study are larger than the more polar ones. This is done to compensate the poorer coverage at low latitude due to the very elliptical orbit of the spacecraft.

Table 1: Statistics of the CO observations for the different latitude bins and on each side of the terminator for both hemispheres.

	North Hemisphere		South Hemisphere	
	AM	PM	AM	PM
0°-30°	8	9	12	18
30°-60°	5	3	16	21
60°-70°	3	7	6	6
70°-80°	14	14	4	5
80°-90°	45	29	6	7
Total	75	62	44	57

3. Results

Individual vertical profiles will be discussed, as well as average profiles obtained for the different latitude bins considered in this study.

A previous analysis of the short term variability of CO [5], has indicated high variability from day to day but also from one occultation season to the other. Timescales involved are small, defined on a day-to-day basis. The region sounded by SOIR (65-150 km) corresponds to a region where different circulation patterns coexist: the SS-AS driven by strong diurnal temperature gradients, which is active essentially above 120 km, and the retrograde zonal circulation. The latter is active in the lower atmosphere (below 70 km). However it has been suggested that gravity waves, generated in the unstable cloud region, could force the retrograde zonal flow well above 70 km extending up to higher altitudes.

A clear correlation was found between CO abundance, CO_2 and temperature for altitudes above 110 km. The correlation is less pronounced for lower altitudes. This confirms that above 110 km the main process is the photodissociation of CO_2 to CO. This is also a confirmation that other processes in which CO is involved, such as cloud formation or participation in the catalytic cycles to recombine into CO_2, occur at lower altitudes.

4. Summary and Conclusions

CO densities and vmr have been measured by the SOIR instrument on board Venus Express on a regular basis since the beginning of the mission. Observations cover both hemispheres from 90°S to 90°N latitudes, but are all obtained at the terminator (LST 6 am and 6 pm). We have investigated the latitudinal variations of CO, as well as the time evolution, over short and long time period. We have analysed the diurnal evolution of the CO abundance at different altitudes. We have also shown some results from a previous study focused on the short term variability of CO [5] to get a complete picture of the CO abundance on Venus.

Acknowledgements

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Variability of SO_2 and HDO at the cloudtop of Venus from high-resolution infrared spectroscopy

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Abstract

Since January 2012, we have mapped the SO_2 and HDO mixing ratios at the cloudtop of Venus using the Texas Echelon Cross Echelle Spectrograph (TEXES) at the Infrared Telescope Facility (IRTF). The HDO maps appear homogeneous over the Venus disk. In contrast, the SO_2 maps show strong variations over the disk and within a time scale of two hours. Both molecules show long-term variations with no apparent correlation between the two species.

1. Introduction

SO_2 and H_2O play a key role in the atmospheric chemistry of Venus [1]. Both molecules are strongly depleted at the level of the main cloud due to SO_2 photodissociation and H_2SO_4 condensation processes. As a complement to the Venus Express campaign, we have started an observing program using TEXES at IRTF to map SO_2 and HDO at the cloudtop. Results of the January and October 2012 runs have been published in [2, 3]. We present here the results of the following runs (February and July 2014, March 2015).

2. Observations

We selected the 1343-1353 cm^{-1} range (7.4 μm) where weak transitions of CO_2, SO_2 and HDO can be found. At this wavelength, the radiation probes the cloud top at an altitude of about 63 km. We mapped the SO_2 and HDO mixing ratios by making the ratio of the line depth of these molecules with respect to the CO_2 line depth. The maps were achieved by orienting the 8-arcsec slit along the north-south celestial axis and moving it from west to east by 0.5 arcsec steps to map the whole planet. The diameter of Venus ranged from 12 arcsec (July 2014) to 33 arcsec (February 2014), so several scans were recorded from north to south in order to map the whole planet. The resolving power was 8×10^4. As in the case of our October 2012 observations, we selected a CO_2 transition at 1345.2 cm^{-1}, SO_2 transitions at 1345.12 and 1345.28 cm^{-1}, and a HDO transition at 1344.90 cm^{-1}.

3. Results

Figure 1 shows maps of HDO recorded between October 2012 and March 2015. It can be seen that the maps are globally uniform, with a drop of intensity by about a factor of 2 in July 2014, observed during two consecutive days. The mean H_2O mixing ratio, assuming a D/H value in Venus of 200 SMOW (Standard Mean Ocean Water) [4] is about 1.0 +/- 0.5 ppmv, in agreement with previous ground-based and space measurements [4-7].

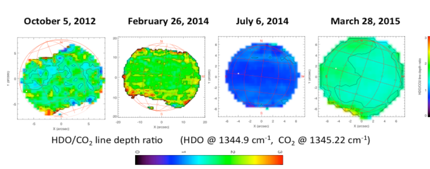

Figure 1: Maps of the HDO/CO_2 line depth ratio at the cloudtop of Venus between October 2012 and March 2015. A HDO/CO_2 line depth ratio of 1.5 corresponds to a H_2O mixing ratio of about 1 ppmv [3, 4]. A drop of the water content by a factor 2 is visible in the February 2014 dataset.

Figure 2 shows maps of SO_2 recorded in July 2014 and March 2015. Both sets of maps show strong spatial variations (as already observed in 2012 [2, 3]). The disk-averaged mixing ratio of SO_2 is about constant. Temporal variations (also observed in 2012) are noticeable on a time scale of two hours.

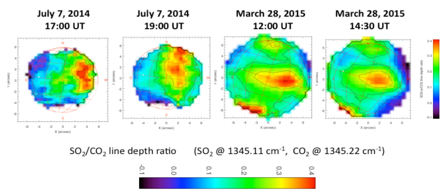

Figure 2: Maps of the SO_2/CO_2 line depth ratio at the cloudtop of Venus in July 2014 and March 2015. A SO_2/CO_2 line depth ratio of 0.2 corresponds to a SO_2 mixing ratio of about 120 ppbv at the cloudtop [3].

The SO_2 mixing ratios are in overall agreement with other past and recent measurements in the same altitude range [6, 8 – 10]. All studies illustrate the high spatial and temporal variability of SO_2.

Figure 3 shows the long-term variations of the SO_2 and H_2O (inferred from HDO) mixing ratios at the cloudtop, between January 2012 and March 2015. The HDO curve shows a moderate depletion (by a factor of about 2) in July 2014. The SO_2 curve is constant over time, except for a drop by a factor 3 (significantly outside the noise level) in February 2014. It is interesting to note that there is no correlation between the SO_2 and H_2O curves. In the same way, the absence of spatial and short-term variations in the HDO maps illustrate that different processes are at work in the behaviors of the two species at the cloudtop. In the case of SO_2, its short photochemical lifetime is probably responsible for its high spatial and short-term variability.

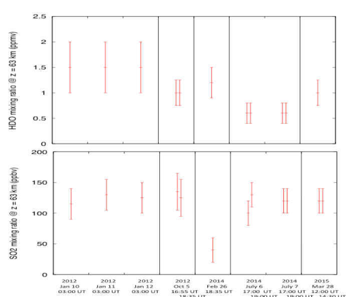

Figure 3: Temporal variations of the disk-integrated SO_2 and HDO mixing ratios at the cloudtop of Venus between January 2012 and March 2015.

Acknowledgements

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EPSC Abstracts
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Sulfur Dioxide variability in the Venus Atmosphere

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Abstract

Recent observations of sulfur oxides (SO_2, SO, OCS, and H_2SO_4) in Venus' mesosphere have generated controversy and great interest in the scientific community. These observations revealed unexpected spatial patterns and spatial/temporal variability that have not been satisfactorily explained by models. Particularly intriguing are the layer of enhanced gas-phase SO_2 and SO in the upper mesosphere, and variability in the maximum observed SO_2 abundance and the equator-to-pole SO_2 abundance gradient, seemingly on multi-year cycles, that is not uniquely linked to local time variations. Sulfur oxide chemistry on Venus is closely linked to the global-scale cloud and haze layers, which are composed primarily of concentrated sulfuric acid. Consequently, sulfur oxide observations provide important insight into the ongoing chemical evolution of Venus' atmosphere, atmospheric dynamics, and possible volcanism.

Existing observations have been obtained using multiple platforms, observing techniques, and wavelengths. Each has its own unique strengths and limitations. Although there is strong agreement on some features, there are significant unresolved apparent disagreements among current observations and between observations and models. These apparent disagreements need to be analyzed and assessed carefully to synthesize a clear understanding of sulfur oxide chemistry on Venus. These investigations have been performed via 1) the comparison and validation of observations, from past missions, Venus Express, Earth-based telescopes, and the Earth-orbiting Hubble Space Telescope; and 2) modelling of the SO_2 and sulfur-oxide family photochemistry. The current study has been carried out within the frame of the ISSI International Team entitled 'SO_2 variability in the Venus atmosphere'.

1. Introduction

SO_2 is strongly related to the formation of the clouds and haze on Venus, which are composed of sulfuric acid combined to water complexes. Presence and variations of SO_2 could be the proof of a possible volcanism on Venus. The most intriguing are discrepancies among different observations, and the suspected long-term variations of the SO_2 abundance observed on the scales of several years, in particular during Pioneer Venus Orbiter and Venus Express missions. Similar trends are also observed in the super-rotation period and circulation patterns, which suggest that these aspects may be more strongly coupled than expected.

2. Data sets

In this study, we tried to reconcile the following different observations: previous measurements performed by the Venera probes and Pioneer Venus, as well as more recent observations carried out from Earth or from space-borne instruments, either those on board Venus Express (SPICAV, SOIR, and VIRTIS) or being part of the Hubble Space Telescope suite of instruments.

A first step was the direct comparison of SO_2 abundances obtained by these various instruments. This led to a better understanding of the limitations of each technique used to determine the SO_2 abundance, either at localized altitudes, as profiles or as integrated column values. In a next step, the SO_2 abundance was investigated in terms of spatial and temporal variability, on small/short and large/long scales, as well as relative to local time.

For example, the dayside the gas abundance detected in the 60-100 km altitude range was observed to vary by a factor of 2-5 as a function of local time; similarly, one-to-one comparison of observations made in the 60-100 km altitude range at specific latitudes and local times indicates that the SO_2 gas abundance varied by a factor of 2-10 on the time scale of a few Earth days.

At the cloud tops the long-term average of the SPICAV data shows that during the VEx campaign the 70-80 km dayside SO_2 gas abundance was typically highest in the equatorial region and decreased with increasing latitude. At the same time, both the SPICAV and HST observations indicate that the latitudinal SO_2 gradient in the 70-80 km altitude region was variable, and that the variation in the latitudinal gradient was dependent on the overall abundance of the SO_2 gas.

Photochemical and dynamical modelling schemes investigating the observed vertical and horizontal (both latitudinal and local time) gas density distributions are underway and we will present a summary of the most recent findings.

4. Summary and Conclusions

An ISSI international team has been built in view of considering different aspects of sulfur chemistry on Venus. This includes comparison and validation of observations, from past missions, from Venus Express, from the Earth, and from Hubble Space Telescope, modelling of photochemistry and of other dynamical processes in which the sulfur family is involved. We will consider not only SO_2, but also SO and other constituents involved in its cycle. Reference density and Volume Mixing Ratio (VMR) fields will be constructed from the detailed analysis and comparison of data. These will be included into the next generation of the VIRA references atmosphere.

Acknowledgements

The authors wish to thank the International Space Science Institute (ISSI) for their fruitful support. Most of the authors were members of the ISSI International Team “Sulfur Dioxide variability in the Venus atmosphere” who met during the 2013-2015 in the facilities of ISSI in Bern, Switzerland.

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A Retrospective Look at the Collected Results on the Large Scale Ionospheric Magnetic Fields at Venus

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Abstract

We revisit the collected large scale ionospheric magnetic field results obtained by the Pioneer Venus Orbiter (PVO) and Venus Express (VEX) missions to ask how much we really understand about that field's global structure. To assist in this assessment we make use of several previously described MHD simulations of the solar wind interaction that reproduce its other observed features. These comparisons help to support our conceptual pictures in some cases, and to raise questions in others.

1.Introduction

The PVO mission provided the first look at the ionospheric magnetic fields of Venus, including their spatial patterns and their changes with external conditions (e.g. see the review in [1] and references therein). PVO sampled the fields near its ~150 km periapsis centered around 15 deg. N latitudes, primarily during the active period of the solar cycle. The availability of many orbits of low altitude observations (~600) made it possible to develop a conceptual picture of those fields. The VEX mission made its deepest measurements (to ~130 km) around its near-north-polar periapsis, during the recent pre-end-of-mission aerobraking phase. These VEX measurements were also obtained around solar maximum, with the difference that the present cycle has been weaker in terms of both its solar EUV flux and solar mass flux/interplanetary field strengths. Both sets of measurements show the apparent penetration of nearly horizontal large scale magnetic fields from the magnetosheath/magnetic barrier into the ionosphere, whose nominal boundary ranges from ~250 km to ~800 km, depending on solar wind pressure and ionospheric pressure [1,2].

It is not likely that the Venus ionospheric field will be observed again for some time, making an overall revisit of this topic timely –especially in light of broader interest in induced magnetospheric interactions and weakly magnetized planetary bodies. We also have the results of several global MHD simulations of the Venus-solar wind interaction that have been run using the BATS-R-US code in both single fluid, multispecies, and multifluid forms [3]. We use these as inspiration for investigating features found in the combined, orbitally biased, data sets, as well as for determining the extent to which the model assumptions capture the physics of this part of the solar wind interaction. Among the features re-examined are field structures in the nightside and their magnetic connection to the dayside draped fields, and the extent to which the penetrated magnetic barrier field can truly be regarded as a 'belt' [4,5].

2. Approach

We manipulate the observations in a statistical sense, in the VSO coordinate system and its spherical counterpart. We eliminate difficulties of not having an upstream solar wind monitor and associated statistics reductions inherent in organizing the data by interplanetary field orientation by working with the complete data set as measured. This allows us to look for patterns such as statistical relationships between vector components, drawing out behaviors associated with the average (toward and away Parker Spiral) interplanetary magnetic field directions, and solar wind and ionospheric pressures. We make graphical comparisons of key components of the field with their model counterparts, examining specific features such as the severity of field draping and the large scale field altitude profiles at the poles compared to lower latitudes. We ask whether there are counterparts of the nightside ionospheric holes in the model and their relationship to the large scale dayside field. These and other such comparisons provide a worthwhile test of our real understanding.

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Retrieval and study of near-infrared surface emissivity maps of Themis Regio on Venus with VIRTIS-M (Venus Express)

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Abstract

Surface emissivity maps of Themis Regio on Venus have been derived from nightside radiance spectra acquired by VIRTIS-M-R aboard Venus Express to explore the region's geology. The emissivity retrieval bases on a new approach combining a full radiative transfer model to simulate the spectra and a multi-spectrum retrieval algorithm to retrieve parameters that are common to a set of spectra. Assuming geologic activity to be negligible during the observations, the emissivity maps at 1.02 µm, 1.10 µm, and 1.18 µm were retrieved as parameter vector that is common to many spectral image cubes covering Themis Regio. This approach provides the so far most precise semi-quantitative emissivity data at Themis Regio in the near IR range. Resulting emissivity maps display clear spatial variations relative to a referance value. We discuss the relevance of these variations to geologic structures and surficial properties.

1. Introduction

Little is known about Venus' surface composition because the dense atmosphere prevents direct observations of the surface at visible and IR wavelengths. The visible and infrared thermal imaging spectrometer (VIRTIS) aboard ESA's Venus Express mission provided new three-dimensional data of the Venusian atmosphere and information on global surface properties [1-4]. This includes systematic studies of the nightside thermal emissions of Venus in the near infrared spectral transparency windows between 1.0 and 1.2 µm. A first application of the new retrieval method described in section 2 was performed with the VIRTIS-M-IR measurements at Themis Regio on Venus. VIRTIS-M-IR data were reasonably binned to match the achievable spatial resolution of about 100 km [5], and retrieved emissivity maps were referenced to Magellan topography and a geologic map [6]. These data can be used to determine information about additional surface properties.

2. Method

Venus surface emissivity retrieval bases on a detailed radiative transfer forward model [7-10], a multi-spectrum retrieval technique (MSR) [9-11], and a detailed error analysis [10]. The forward model simulates the radiance spectra. It considers absorption, emission, and multiple scattering by gaseous and particle constituents of the atmosphere. MSR can retrieve parameters that are common to a set of spectra. Moreover, it regularizes the retrieval by incorporation of available *a priori* mean values and standard deviations of parameters to be retrieved and physically reasonable spatial-temporal *a priori* correlations. The retrieval pipeline results in emissivity maps relative to a reference value. Main findings for Themis Regio are discussed in section 3.

3. Results

The relative emissivity map of Themis Regio at 1.02 µm is derived from a 64-repeition data set and shown in Figure 1. Themis Regio is a highland region classified as a corona-dominated hotspot rise [12] and related to long duration, non-simultaneous, small-scale upwellings. Gravity data and topographic swell suggest the region is likely underlain by an active plume with ongoing surface deformation due to growth of the rise [13]. The target area includes geologic structures like the Shiwanokia Corona with steep sided domes, Shulamite Coronae, Abeona and Mertseger Mons, impact craters like Kenny, Aksentyeva, and Sabin with a dark parabola, graben, and wrinkle ridges.

measurement data available that were used for these studies.

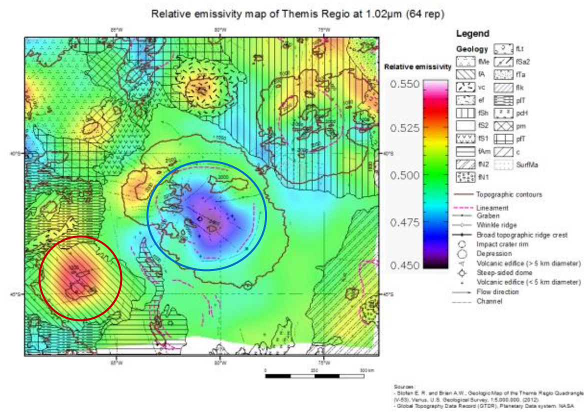

Figure 1: 1.02µm emissivity map [6] overlaid onto the geologic map. Right: Legend, geology, and color bar for the retrieved emissivity. Red circle: Abeona Mons; blue circle: Shiwanokia Corona.

The map displays relevant variations that indicate the heterogeneity of Venus' surface emissivity. Red (increased values relative to the reference emissivity) and blue (decreased values relative to the reference emissivity) colored areas show reliable and relevant differncies compared to their surroundings (yellow, green, cyan). In general, these emissivity "anomalies" can be caused by local changes in composition, age, and/or textural differncies of the surface (smooth fresh vs. rough old and weathered areas). Shiwanokia Corona has areas of low emissivity (blue circle in Figure 1). The complexity in this region might suggest long histories and an apparently older coronae [14]. In contrast, an increase of emissivity might be related to a higher iron content of mafic minerals or smooth and relatively fresh material. One example is the radar-dark Abeona Mons (Figure 1, red circle). Its high emissivity signature might rather correlate with stratigraphically relatively young units interpreted to be of volcanic origin, consistent with findings in [15]. Further results of emissivity retrieval are presented and discussed.

Acknowledgements

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Potential Vorticity of the South Polar Vortex of Venus

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Abstract

The atmospheric vortex at the southern pole of Venus is highly variable in morphology and unpredictable in its dynamical behavior. Using infrared images from the VIRTIS-M instrument onboard Venus Express we have built maps of Ertel's potential vorticity at the lower and upper clouds (altitudes ~41-45km and ~55-62km above the surface). For this purpose, we have combined the wind field at both clouds' levels and the three-dimensional thermal structure that we previously measured [1, 2].

1. Ertel's Potential Vorticity

We have considered three widely different vortex morphologies (see Figure 1) in order to better understand the relation between the vortex's morphology, its dynamical properties and its variations at short and long timescales.

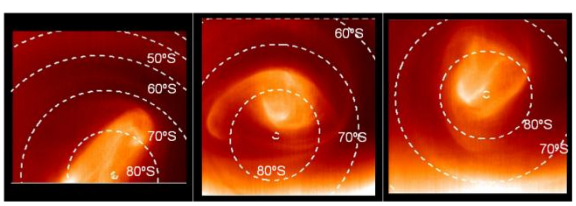

Figure 1: Three different configurations of the South Polar Vortex of Venus as observed by the VIRTIS-M-IR instrument in ~5µm images. Reference [2] shows that these radiance images are highly correlated with the thermal structure of the atmosphere at the cloud top.

For an inviscid atmospheric flow (neglecting friction) and in the absence of sinks of sources of potential vorticity from diabatic heating, the Ertel's potential vorticity (EPV) is a conserved quantity that can be used as a tracer of fluid motions [3] being therefore an appropriate quantity for diagnostic studies of the atmospheric dynamics [4]. The general definition of Ertel's potential vorticity (EPV) under the hydrostatic approximation can be written as [3, 4]:

$$q = \frac{\overrightarrow{\omega_R}+2\vec{\Omega}}{\rho}\nabla\theta \sim (\zeta_\theta + f)\left(-g\frac{\partial\theta}{\partial P}\right) \quad (1)$$

where $\overrightarrow{\omega_R} = \nabla \times \vec{U}$ is the vorticity of the wind vector $\vec{U}$, $\vec{\Omega}$ is the angular rotation speed of the planet, ρ is the density, and θ is the potential temperature. $f = 2\Omega \sin\phi$ is the Coriolis parameter (with ϕ being latitude), ζ_θ is the relative vorticity calculated on an isentropic surface (constant θ), P is the pressure, and g is the gravitational acceleration.

Therefore, the horizontal spatial structure of EPV depends on $\zeta_\theta(x,y)$ through the wind velocity field and on $\frac{\partial\theta}{\partial P}(x,y)$ through the temperature field. The later term is related with the static stability of the atmosphere and is always negative on the area covered by the Venus vortex [2, 5].

2. Results

Our analysis shows that the vortex is a vertically depressed structure when observed in isentropic surfaces between 55 and 85km altitude. At the upper cloud's level (55-62km) the vortex sinks 2-3km over horizontal distances of 240-330km (Figure 2), with smooth altitude variations inside the warm vortex that correlate with structures seen in the thermal images.

The EPV value range obtained at the upper cloud's level is -1–5 (x10^{-6} K m^2 kg^{-1} s^{-1} ≈ 1 P.V.U., *potential vorticity unit*), while at the lower cloud's level (~41-45km) the EPV decreases two orders of magnitude (-2–8 x10^{-2} P.V.U.).

The horizontal distribution of EPV at the upper cloud's level does not retain the structure seen in the radiance images or in the temperature maps (Figure 1), but resembles the distribution of the relative vorticity, which is determined purely from tracked motions [1]. At the lower cloud's level, where the radiation coming from space hardly penetrates, the thermal structure is computed from latitudinal analyses of Pioneer Venus, VIRA and Venus Express radio occultation data [5] and tends to homogenize the structure seen in the relative vorticity maps. In both cloud layers, the kinetic component dominates with respect to the thermal structure.

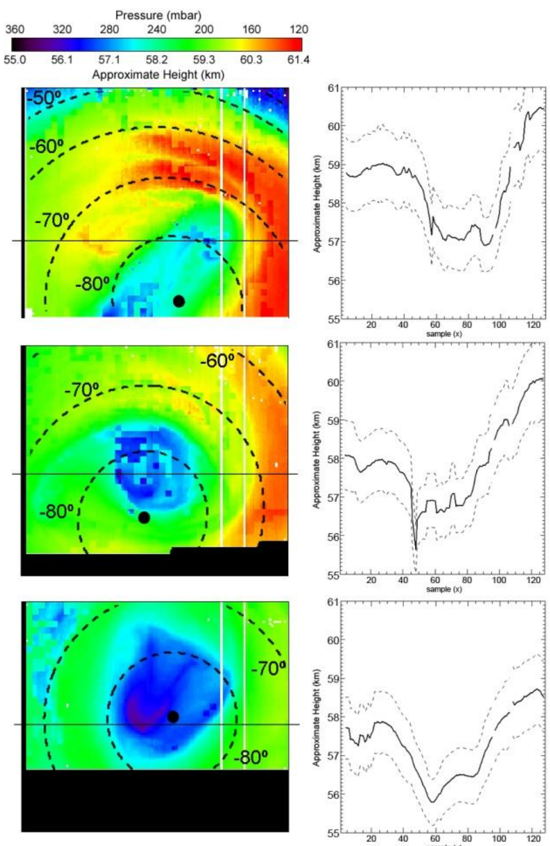

Figure 2: Altitude variation of the 330K isentropic surface (left) and over the solid lines displayed in the left columns (right) on orbits 038 (top), 310 (middle), and 475 (bottom). Dashed lines depict the altitude uncertainty range.

3. Conclusions

The global structure of the EPV at the upper cloud's points to a weak ring of potential vorticity without any strong latitudinal gradient, as should be expected in the presence of a mixing barrier. However, local minima and maxima of EPV are found close to each other with differences of up to 4 P.V.U. The annular shape in potential vorticity is a trait shared in common with Mars' polar vortices, while the vertically extended structure of the Venusian vortex is in common with Earth's polar vortices. Apparently, Venus' South Polar Vortex is a feature intermediate in its characteristics between Mars' and Earth's polar vortices.

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EPSC Abstracts
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European Planetary Science Congress 2015

Simulation of Venusian atmosphere by AFES (Atmospheric general circulation model For the Earth Simulator)

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Abstract

We have developed an atmospheric general circulation model (AGCM) for Venus on the basis of AFES (AGCM For the Earth Simulator) and performed a very high-resolution simulation. A superrotation consistent with observations is reproduced with a realistic solar heating. Baroclinic waves appear in a weakly stratified layer with large vertical shear of the basic zonal flow at the cloud level. Rossby and Kelvin waves generated in the model are consistent with observations. Furthermore, a realistic polar cold collar is reproduced in the polar region. Spectral analyses of the horizontal kinetic energy are also performed in the results with a high-resolution simulation (T159L120).

1. Introduction

So far, low-resolution GCMs have been used to simulate phenomena in the Venus atmosphere. This is mainly because of the extremely long spin-up time to generate a superrotation from a motionless state. Furthermore, in order to generate a superrotation, most of the previous GCM studies have included unrealistic strong solar heating and static stability. In the present study, we have constructed a new model based on AFES to perform realistic high-resolution simulations of the Venus atmosphere.

Many observational studies have reported signals of planetary-scale Rossby- and Kelvin-type waves at the cloud top. However, the waves obtained in the previous numerical studies are not consistent with observations. This is partly because the fast mean zonal flow has not been reproduced realistically in the models. Further, the weakly stratified layer in the cloud layer has been neglected in their models. Observational studies also suggest that small-scale gravity waves play important roles at the cloud level.

In the present study, we perform simulations with very high resolutions to investigate properties of disturbances in a wide range of scales in the Venus atmosphere. The neutral waves and the polar cold collar are important targets to take advantage of a high resolution model.

2. Model

AFES simulations are performed with simplified physical processes adopting the values of physical constants appropriate for Venus. The experimental settings basically follow those of the previous AFES simulations [1]. The highest resolution used in the present simulations is T159L120, which is equivalent to a horizontal grid size of about 79 km. The vertical domain extends from the ground to about 120 km with almost the constant grid spacing of 1 km. Simulations with T63L120 and T42L60 resolutions, are also performed.

The physical processes adopted in the model are vertical eddy diffusion with a constant diffusion coefficient of 0.15 m2/s, the Newtonian cooling, and the Rayleigh friction at the lowest level representing the surface friction. In the upper region above about 80 km, a sponge layer is assumed. In addition, the model includes a 4th-order horizontal diffusion with an e-folding time for the maximum wavenumber of about 0.01 days for T159, 0.03 days for T63, and 0.1 days for T42 simulations. The coefficients of the Newtonian cooling are based on the previous study. The equilibrium temperature distribution toward which temperature is relaxed by the Newtonian cooling is the prescribed horizontally uniform temperature distribution based on observations. We adopt a realistic profile of solar heating. Vertical and horizontal distributions of the solar heating are based on Tomasko et al. [2].

The vertical temperature profiles of the initial conditions are constructed based on the observed vertical distribution of static stability. The initial condition for wind velocity is zonally symmetric, solid-body superrotating flow, which is determined by the gradient wind balance; zonal velocity at the equator linearly increases from zero at the ground up to 100 m/s at the altitude of 70 km, and above there the atmosphere is in a solid-body rotation with the same speed as that at 70 km. From this initial condition, time integration is performed for four Earth years for T159 and T42 simulations and ten Earth years for T63 simulation.

3. Results

Starting from the idealized superrotation, the model atmosphere reaches a quasi-equilibrium state within one Earth year. The zonal-mean zonal flow, which is accompanied with weak mid-latitude jets, has almost constant velocity of 120m/s in latitudes between 45°S and 45°N at the cloud top levels. This meridional distribution of the zonal flow agrees very well with observations. Strong latitudinal temperature gradient is produced at 45–70 km, where the temperature difference between the equator and the pole is more than 25 K. Strong baroclinicity, i.e., large vertical shear of the zonal flow is maintained at mid-latitudes in the weakly stratified layer extending from 50 to 70 km by the solar heating.

The horizontal structure of the baroclinic waves observed at 70 km for T63 simulation is shown in Fig. 1. In mid-latitudes between 30° and 60° the zonal wave number 1 component of geopotential height is predominant. These disturbances are in phase with temperature deviations at the altitude of 60 km (color). The result suggests that so-called Rossby waves observed at the cloud top are generated by the baroclinic waves excited at around the altitude of 60 km. The period of the waves is about 5.8 days. These wave characteristics are in good agreement with the observed so-called Rossby waves.

Below the altitude of 50 km, planetary-scale waves with zonal wave number 1 appear in the low latitudes between 30°S and 30°N, where zonal winds are predominant. The horizontal structure of the equatorial waves is similar to the so-called Kelvin waves. The period of the equatorial waves is about 6.2 days which is consistent with those observed at the levels of 50–60 km. These results are summarized in [3].

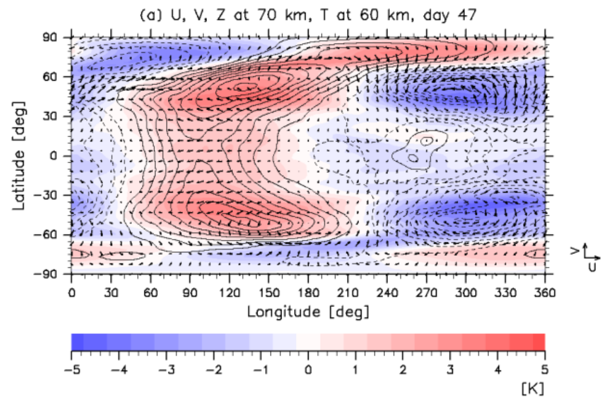

Figure 1: Horizontal distributions of geopotential height (black contours) and horizontal flow (black vectors) associated with the short-period disturbances at 70 km height, and temperature deviation at 60 km height (color shades) at day 47 from ten Earth years. A band-pass filter between the periods of 2 and 8 Earth days is applied. Contour intervals are 25m and vector units are 50m/s.

4. Summary and Conclusions

We have performed a very high-resolution simulation for Venusian atmosphere by AFES. Rossby and Kelvin waves generated in the model are consistent with observations. The results indicate that the realistic vertical distribution of static stability with thermal tides and sufficient model resolution are crucial for reproducing the Venus atmosphere.

Acknowledgements

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EPSC Abstracts
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Thermal structure of Venus upper atmosphere by a self-consistent ground-to-thermosphere GCM

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Abstract

We present here the thermal structure of the upper atmosphere of Venus predicted by a full self-consistent Venus General Circulation Model (GCM). The Venus GCM developed at *Laboratoire de Meteorologie Dynamique* (LMD) [1] is currently operational up to 150 km and it is one of the leading models in the community. Recent improvements (i.e the inclusion of physical processes relevant in the upper atmosphere, the coupling with a photochemical model) contributed to a better understanding of the upper mesosphere/lower thermosphere of Venus. Our aim is to describe the role of radiative, photochemical and dynamical effects in the observed thermal structure of those upper layers, and to evaluate the impact of current parameterisations and theoretical uncertainties on the temperature fields. Several sensitivity tests will be performed to understand the data-model discrepancies and to improve the comparison.

1. Introduction

The successful European Space Agency's Venus Express (VEx) mission marked the beginning of a new era for the exploration of our neighbour planet. After eight years in orbit (2006-2014) exceeding its planned life, a considerable amount of data from several instruments on board were collected. Direct measurements taken by aerobraking manoeuvres at the end of the mission, together retrievals by VIRTIS ([2]) and SPICAV-SOIR ([4, 3]) above 90-100 km provided an extremely valuable piece of information on local atmospheric densities and temperature of a region very difficult to sound, and surprisingly more variable than expected. In addition to this, a number of ground based observational campaigns have noticeably complemented the satellite observations during VEx mission. The scientific community has been doing several efforts to carry out a systematic inter-comparison and validation of both satellite and ground-based telescope measurements within an international context of several international projects. All those efforts contribute to an unprecedented insight into the complex dynamical mechanisms going on the atmosphere of our sister planet. Nevertheless, VEx also raised new challenging questions to be answered. Sophisticated climate models and synergies with the data analysis are fundamental to interpret the observed results and to help building a consistent picture of the spatial and temporal evolution of the Venus atmosphere.

2. An improved Venus LMD-GCM

The Venus GCM developed at LMD [1], based on the tools and experience gathered for the GCM of the Earth's, has been used to study the role of thermal tides in the super-rotation of Venus atmosphere and to compute consistent temperature fields, from the surface up to 100 km, which helped to interpret recent VEx measurements. In the last 5 years, the Venus LMD-GCM has been noticeably improved by the inclusion of a self-consistent radiative transfer module, the ongoing development of a microphysical module, the inclusion of a photochemical model and by the extension up to the lower thermosphere (150 km). The vertical extension of the model mainly consisted in the implementation of physical processes relevant to the thermal balance of the upper atmosphere of Venus from 100 to 150 km. In particular, the role of non-LTE processes, EUV heating and thermal conduction has be taken into account, and proper parameterisations for GCMs implemented. Here we adopted the methodology developed for the Mars GCM ([5]), consisting of 1-parameter analytical formula to reproduce the solar heating rates in those upper regions, and a simplified non-LTE model for the 15-μm cooling. It is assumed that the net solar absorption depends mainly on the density of the atmosphere, and to a smaller degree on the solar zenith angle, thermal structure and atomic oxygen abundance. EUV absorption is also included assuming an efficiency of 21 % and the variation of the EUV solar flux with the solar cycle is considered. Molecular viscosity and molecular diffusion also have an impact on the winds and on the composition of the atmosphere, respectively. Thanks to these improvements the current LMD Venus GCM is actually able to provide a full self-consistent and quantitative description of the Venusian upper atmosphere and to perform a more comprehensive comparison with available dataset.

2.1 Results: thermal structure

Figure 1 shows the mean temperature field after 10 venusian days (about 6 terrestrial years) at equatorial regions (30S-30N), plotted here as function of local time (hours) and pressure (Pa). This simulation is performed by the LMD Venus GCM fully-coupled, for the first time up to about 150 km, with the LATMOS photochemical model ([6]). The predicted structure is mainly a combination of radiative and dynamical effects. The strong local maximum observed during daytime is due to solar absorption by CO_2 near-infrared bands (1-5 μm) between 1-0.1 Pa, and a local minimum (at about 10^{-2}-10^{-3} Pa) is produced by thermal cooling via CO_2 non-LTE transitions around 15μm. Above 10^{-3} Pa (140 km altitude) EUV absorption by CO_2, O and a number of minor species, together with thermal conduction, dominate. The nighttime warm layer produced by subsidence of day-to-night circulation air is clearly observed around the anti-solar point. Those main features have been also recently observed in the upper atmosphere of Venus by VEx. Despite that, a number of data-model discrepancies (e.g different pressure level and intensity of the local maximum, colder morning terminator, etc) indicate that radiative, photochemical and dynamical effects have to be further investigated. We are currently working to tune the model in order to produce reference simulations capable to reproduce, as accurately as possible, the observed vertical and horizontal structure of the temperature in the upper mesosphere/lower thermosphere of Venus. The impact of current parameterisations and theoretical uncertainties (i.e solar heating rates, relaxation/collisional coefficients, EUV efficiency) on the temperature fields will be evaluated and sensitivity tests performed to understand the data-model discrepancies and to improve the comparison with all available dataset.

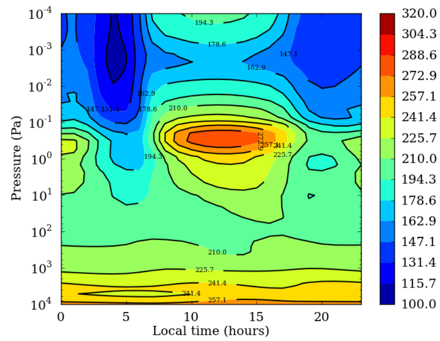

Figure 1: Local time-pressure cross sections of "mean" temperature fields predicted by LMD-VGCM after 10 Venus days, averaged at equatorial latitudes 30S-30N.

Acknowledgements

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EPSC Abstracts
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European Planetary Science Congress 2015

Analysis of the radiative budget of Venus atmosphere based on infrared Net Exchange Rate formalism

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Abstract

The thick cloud cover present in the atmosphere of Venus between roughly 47 and 70 km of altitude plays a crucial role in the radiative balance of this system, by reflecting more than 75 % of the incoming solar flux back to space, absorbing half of the remaining flux, and being also optically thick over most of the infrared spectral range. The temperature profile of the atmosphere of Venus is characterized by a very hot troposphere from the surface ($\sim$735 K) to roughly 60 km altitude, in the middle clouds. The strong greenhouse effect is provided by the 92 bars of CO_2 that is the main constituent of the atmosphere and by the thick cloud layer.

Taking advantage of the Net Exchange Rate formalism we use for the infrared radiative transfer in the atmosphere of Venus [1], a detailed analysis of the energy exchanges is proposed here. The extinction coefficients in each layer and wavelength narrow band include (1) the gas absorption opacities that are computed with *kspectrum* (see *http://www.meso-star.com/en_Products.html*); (2) collision-induced absorption (CIA) continuum; (3) cloud opacities based on the cloud model retrieved from VIRTIS/Venus Express and PMV/Venera 15 data by [2].

The computation of the mean vertical temperature profile is done with a 1-dimensional version of the LMD Venus GCM [3], forced with globally-averaged solar flux.

Balance between solar heating and infrared energy exchanges is analysed for each region: upper atmosphere (from cloud top to 100 km), upper cloud, middle cloud, cloud base, and deep atmosphere (cloud base to surface). All solar energy absorbed below the clouds are reaching the cloud base through infrared windows, mostly at 3-4 μm and 5-7 μm. The continuum opacity in these spectral regions is not well known for the hot temperatures and large pressures of Venus deep atmosphere, but strongly affects the temperature profile from cloud base to surface. From cloud base, upward transport of energy goes through convection and short-range exchanges up to the middle cloud where the atmosphere is thin enough in the 20-30 μm window to cool directly to space. Total opacity in this spectral window between the 15 μm CO_2 band and the CO_2 collision induced absorption has a strong impact on the temperature above the cloud convective layer.

We investigate how sensitive the temperature profile is to uncertainties in gas opacity and discuss the chosen cloud model and solar flux deposition profile that we use for our latest GCM simulations.

Acknowledgements

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European Planetary Science Congress 2015

Dependence of longitudinal distribution of zonal wind and UV albedo at cloud top level on Venus topography from VMC camera onboard Venus Express

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Abstract

A set of UV images obtained by the Venus Monitoring Camera (VMC) [3] was processed by manual and digital methods [2]. Analysis of longitude-latitude distribution of the zonal wind for 49,700 (139 orbit) visual and 457,850 (722 orbit) digital individual wind measurements allowed us to find an influence of Venus topography on change of the average zonal wind in latitude range from 5°S to 15°S from -100.9 m/s in the longitude range 200-300° to -83.4 m/s in the range 60-100° [1].

Investigation of other latitude ranges by using a correlation method demonstrates that correlation shift depends on height of the obstacle streamlined by a flow. Dependence was found for both the average zonal stream and UV albedo averaged for the entire period of observations.

Introduction

An unprecedented number of UV images of upper clouds of Venus, obtained by VMC on the Venus Express spacecraft was used to study the circulation of the mesosphere [2, 4]. The long observation period (from 2006 to 2014) and good longitude-latitude coverage by single measurements allowed us to eliminate short-periodic changes in the velocity component in the zonal flow and to focus on the study of the slow-periodic component. We managed to trace the influence of topography of the underlying surface on the behavior of the mean zonal flow and the average UV albedo for a set of latitude intervals of 10°.

Results

Longitudinal profiles of surface altimetry, average zonal wind speed and average UV albedo were constructed for each latitudinal range. Then correlations between altimetry profiles and profiles of speed and albedo were considered. Shifts between correlated profiles were defined for the maximum correlation coefficient. Dependence was found between the shift and the maximum height difference of the surface relief in a given latitudinal range.

Figure 1 shows dependence between the maximum height difference and the shift for average zonal stream (visual and digital methods) and albedo at low south latitudes. The shift between the correlated profiles increases when the maximum height difference decreases (to the south of *Aphrodita Terra*) and therefore the influence of the surface relief is delayed. Due to peculiarities in Venus atmosphere circulation, the influence of the meridional component becomes noticeable at 30 °S. It can be seen on Fig. 1 as cease in growth of correlation shift when the height decreases.

In the middle latitudes, circulation becomes more complex, which is reflected in values of correlation coefficients. The coefficients have low values that don't allow us to track the influence of relief.

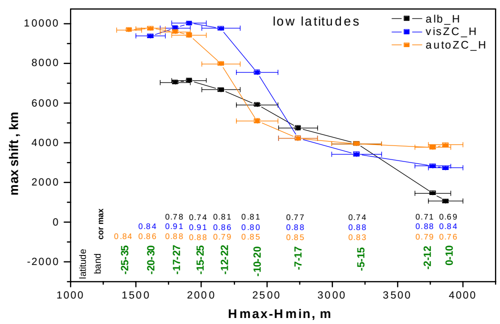

Figure 1. Dependence between the correlation shift and the maximum height difference of the surface relief for a set of latitude intervals 10° wide. The dependence for the average zonal wind by visual method is shown in blue, by digital one in orange, and for albedo in black. This is for **low south latitudes**. Blue, orange and black numbers correspond to correlation coefficients. Green ones – to the latitudinal bands.

In the high south latitudes (Figure 2), due to bad coverage with data, it is only possible to track the dependence between topography and albedo. The latitudinal interval of 60°S -70°S is a rather stable area of transition between the middle-latitude circulation (jet region) and polar circulation where influence of a polar vortex is significant [4]. There is the some height in this area called *Erzulie Mons*. We observe here the same dependence of correlation shift on height, as in latitudes of *Aphrodita Terra*.

Summary and Conclusions

The analysis confirms the influence of the underlying surface topography on the change of speed of the average zonal wind and UV albedo, and also establishes dependence of this influence on the maximum difference of heights in the chosen width interval.

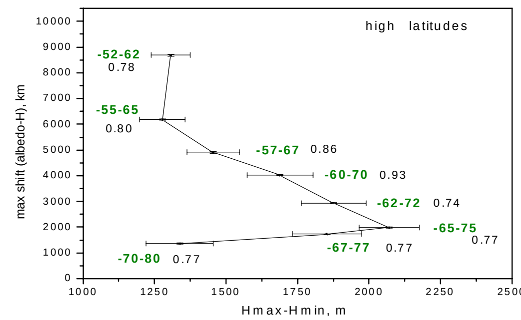

Figure 2. The same as Fig.1, but **for high south latitudes**. Only for albedo.

Acknowledgements

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Cloud tracked winds at the lower cloud level using Venus' night side observations at 2.28 μm with TNG/NICS

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Abstract

We present results based on observations 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 has been to measure the horizontal wind field in order to characterize 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. These observations were part of the network of ground-based observations of Venus coordinated with ESA's Venus Express orbiter for the 2012 Venus transit campaign. Ground-based observations are complementary to orbiter measurements, allowing simultaneous determination of the winds. We will present first results of cloud tracked winds from ground-based TNG observations and winds retrieved from coordinated space-based VEx/VIRTIS observations.

1. Introduction

The atmosphere of Venus is in superrotation, a state in which its averaged angular momentum is much greater than that corresponding to co-rotation with the surface. The circulation up to the cloud tops is characterized by an increasing zonal retrograde wind (in the East-West direction). The wind starts to build up at 10 km and amplifies with altitude, reaching a maximum at cloud tops ($\sim$ 70 km), where the atmosphere rotates about 60 times faster than the surface. Although the clouds are almost featureless in visible light, there are prominent features in UV and infra-red wavelengths. Dominant length scales are larger than 1000 km and few features are smaller than 20-30 km [6]. The cloud deck extends in altitude from 45 to 70 km, and can be divided into three main regions, centered at 48, 54 and 60 km [1]. The lowest of these is the lower cloud, where fundamental dynamical exchanges that help maintain superrotation are thought to occur [2]. The lower venusian atmosphere is a strong source of thermal radiation, with the gaseaous CO_2 component allowing radiation to escape in windows at 1.74 and 2.28 μm. At these wavelengths radiation originates below 35 km, and unit opacity is reached at the lower cloud level, close to 48 km. Therefore, in these windows it is possible to observe the horizontal cloud structure, with thicker clouds seen silhouetted against the bright thermal background from the low atmosphere.

2. Method and results

Our objective is to provide direct absolute wind measurements and a map of cloud distribution at the lower cloud level in the Venus troposphere, in order to complement Venus Express (VEX) and other ground-based observations of the cloud layer wind regime. By continuous monitoring of the horizontal cloud structure at 2.28 μm (NICS Kcont filter), it is possible to determine wind fields using the technique of cloud tracking. We acquired a series of short exposures of the Venus disk. The best 10% of images have been selected, registered to a common coordinate system and co-added to form image A. A subsequent series were taken at a later time, forming image B. Cloud displacements in the night side of Venus, between images A and B, can be computed using both an automated technique [3] and a visual one [5]. This observing strategy was similar to the one used previously by Young et al. [9] and Tavenner et al. [8] at IRTF (Fig. 1). The Venus apparent diameter at observational dates was greater than 32" allowing a high spatial precision. The 0.13" pixel scale of the the NICS narrow field camara allowed to resolve $\sim$ 3-pixel displacements. The absolute spatial resolution on the disk was $\sim$ 100 km/px at disk center, and the (0.8–1") seeing-limited resolution was ~ 400 km/px. By co-adding the best images and cross-correlating regions of clouds the effective resolution was significantly better than the seeing-limited resolution. In order to correct for scattered light from the (saturated) day side crescent into the night side, a set of observations with the Br_γ filter were performed. Cloud features are invisible at this wavelength due to the high optical depth of the gaseous CO_2 component, and this technique allows for a good correction of scattered light [8].

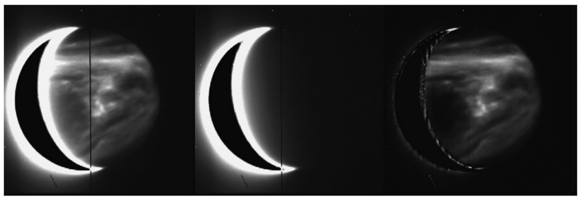

Figure 1: (From Tavenner et al., 2008 [8]): From left to right, a Continuum-K image, a Bracket-gamma, and the result of subtracting a scaled Bracket-gamma image from the one taken in Continuum-K. The black line seen in the first two images is from the IRTF SpeX slit. On these images the dark regions are clouds, the bright regions are optically thinner areas between the clouds that allow thermal emission from the lower atmosphere to escape, and the outlined crescent is the saturated day side of the planet. Images from September 14, 2007.

The data analysis is ongoing. In this poster we will present the progress made and first results of cloud tracked winds for the Venus lower cloud in the night side. With a 3 hr baseline we expect to obtain about 5 m/s resolution on cloud feature velocities [9], which provides a basis for comparison with VEX-VIRTIS measurements [7].

Acknowledgements: We gratefully acknowledge the collaboration of the TNG staff at La Palma (Canary Islands, Spain). We thank the VIRTIS/Venus Express team for support with coordinated observations. We acknowledge support from Fundação para a Ciência e a Tecnologia, projects PEst-OE/FIS/UI2751/2014, POCI/CTE-AST/110702/2009 and Pessoa-PHC exchange program 2011-2013, FCT grants SFRH/BD/66473/2009 and SFRH/BPD/63036/2009 and also the Spanish MICINN for funding support through the CONSOLIDER program ÓASTROMOLÓ CSD2009-00038 and through project AYA2011-23552.

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EPSC Abstracts
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The inversion layer at the tropopause of the Venus atmosphere: new insights from the Radio Science Experiment (VeRa) onboard Venus Express

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Abstract

The inversion layer at the tropopause of the Venus atmosphere is a very common and prominent feature in the vertical temperature profile at higher latitudes. The inversion layer is of particular interest because it separates the stratified troposphere from the highly variable mesosphere. The altitude range of the inversion layer is therefore a likely location for the formation of gravity waves [1]. The Radio Science Experiment (VeRa) onboard Venus Express [2,3] is capable to sound the Venus atmosphere from 100 km downward to 40 km [4,5] and delivered more than 800 vertical profiles of temperature, pressure and neutral number density at almost all local times and latitudes. The tropopause is typically located at 60 km altitude. Spatial changes of the refractive index over a short altitude range lead to multi-path effects which cannot be fully retrieved with common closed-loop recording methods. The development of a new data processing tool based on VeRa open loop data sets provided the necessary frequency resolution to fully resolve multipath effects occurring along a short range of 2 km at the tropopause location.
The inversion layer presents itself up to 15K colder than commonly thought. The new results shall help to find a consistent picture of the Venus' thermal atmosphere structure and therefore help to improve atmospheric models.

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Statistical Survey of Whistler Mode Signals in the Venus Ionosphere: A Proxy Study of Venus Lightning

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Abstract

Venus Express has now completed its more than 8.5 year tenure in orbit around Venus. Throughout the mission it was in a 24 hour elliptical polar orbit with periapsis at ~80° latitude at orbital insertion in 2006. It then precessed near the pole in 2009 and ultimately finished its mission with periapsis at ~72° latitude (Figure 1). For the first few years the altitude of periapsis reached ~250 km above the surface, but later it commonly descended to ~165 km. In mid-2014 the spacecraft performed an aerobraking maneuver in which it descended further into the atmosphere down to ~130 km at its lowest point. Extremely low frequency (ELF) waves generated by lightning were most commonly detected when the spacecraft was near 250 km altitude. Here we present statistics of these lightning-induced ELF waves observed over the entire mission.

1. Introduction

Venus is a strange world when compared with Earth. It has a dense CO2 atmosphere, low water content, and lacks plate tectonics and an intrinsic magnetic field. The surface of Venus is at a temperature of 700 K and a pressure of 90 bar. Cloud layers composed mainly of sulfuric acid exist at an altitude of about 45 to 65 km in contrast to Earth's water-rich clouds, which form in the troposphere at 1 to 10 km. Despite the many differences, it is sometimes referred to as "Earth's twin" due to its similar size, mass, and interior structure. Venus also exhibits familiar terrestrial processes including volcanism and lightning. Due to the high altitude of the Venus cloud layers and the extreme surface pressure, it is not likely that there would be any cloud to ground lightning as this would require an unrealistic amount of charge build up. However, the conditions within the cloud layers of Venus are not unlike those on Earth. The sulfuric acid in the clouds can carry charge similarly to the water in Earth's clouds and they exist at altitudes where the pressure is similar to that of Earth's. Therefore, the cloud layer is where the majority of lightning is expected to occur on Venus. Lightning produces an ELF radio wave that can propagate along magnetic field lines to reach a spacecraft, such as Venus Express, at much higher altitudes.

2. Measurements

The onboard dual fluxgate magnetometer was able to detect ELF signals up to 64 Hz at various altitudes throughout the mission [1]. We analyzed 10 minutes of data about periapsis for each available orbit. The average signal length was 6 seconds with some spanning more than 1 minute. The longer signals are most likely multiple overlapping bursts when the spacecraft was above an electrical storm. These signals, also referred to as whistler-mode waves, were most frequently seen when the spacecraft was at ~250 km altitude. Figure 2 shows the percent of time ELF signals were detected at various altitudes. More than 70% were observed within 200-350 km altitude with a rate of ~1% of the time the spacecraft spent at these altitudes. The maximum detection rate at this altitude is expected due to the slower wave speed here that results in a larger magnetic amplitude for the same electromagnetic energy flux.

3. Figures

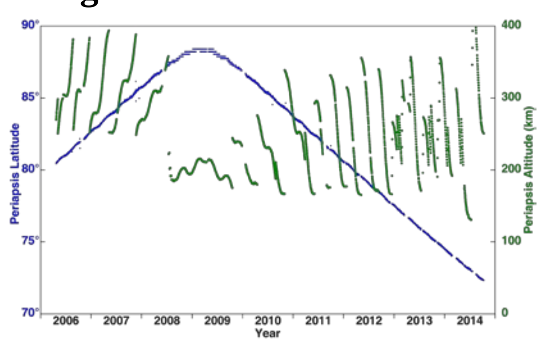

Figure 1: The periapsis of Venus Express has been decreasing in latitude ~3° per year since 2009. The altitude of periapsis lowers due to gravitational forcing and is reraised periodically with thrusters.

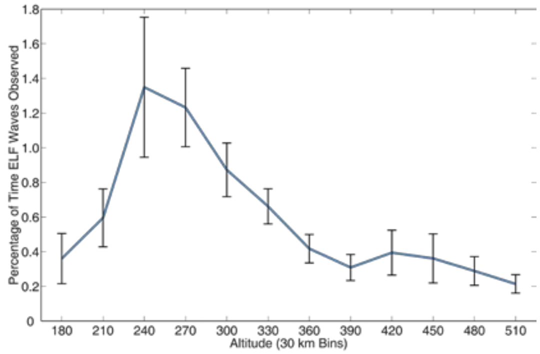

Figure 2: Percent of time of ELF wave activity observed by Venus Express at various altitudes calculated over all local times and latitudes.

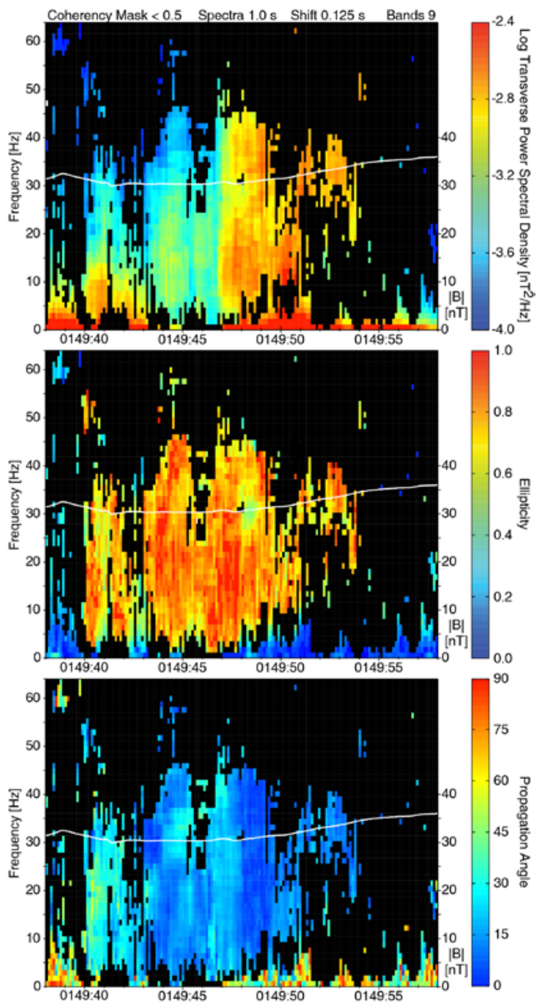

Figure 3: Dynamic spectra of transverse power, ellipticity, and propagation angle for a mid-2012 event. The white line is the total magnetic field strength in nT.

4. Signal Analysis

The Venus Express magnetometer can observe lightning-generated signals up to 64 Hz. Whistler-mode (ELF and VLF in the Earth's ionosphere, but only ELF at Venus) are guided well up to ~¼ of the local electron gyrofrequency. Venus Express should be able to study atmospheric lightning emissions as long as the background magnetic field in the ionosphere is greater than 10 nT thus providing a magnetic pathway through the lower ionosphere. This happens frequently, and Figure 3 illustrates a recent example of the waves seen. We show first the power in the waves as a function of frequency. Note the increase in power at 01:49:47. At this time the field changed directions providing a more efficient path for the waves to propagate. Next is the ellipticity of the waves. Whistler-mode are right-handed, giving a red color to the dynamic spectrum. The third panel is the direction of the wave propagation relative to the magnetic field. Dark blue indicates the waves are propagating parallel to the magnetic field. This event is just one example of more than 100 per Venus year, each confirmed as a whistler-mode wave by the same analysis.

5. Discussion

Venus Express marks the end of the current era of exploration at Venus and currently there are no future approved missions besides the Japanese Akatsuki mission which will attempt a second try at orbital insertion in late 2015. Although Venus Express provided a wealth of data to advance the study of lightning on Venus there is still much to learn, such as temporal and spatial mapping of the actual storms from which these signals are detected. The majority of the lightning generated whistler-mode waves in the Venus ionosphere were observed at ~250 km altitude. As well as being the most effective location for a spacecraft to detect these ELF waves on Venus, this altitude is ideal for radar mapping. A joint radar-lightning mapping mission could be a prime candidate for the next mission to our sister planet.

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On the magnetic configuration near Venus: EOF modeling and statistical analyses based on Venus Express measurements

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Abstract

More than 2000 orbits of Venus Express magnetic field measurements are used for Orthogonal Function (EOF) analysis to study and model the magnetic environment over the Venus northern polar cap. The modeling results extract the dominant coherent variations, separate the known physical phenomena on different EOFs and identify the most important driving factors. EOF1 represents the magnetic draping configuration of IMF Bz component whereas EOF2 is controlled by IMF By component and presents the draping and piling-up of IMF By. Besides, our analysis illustrates an asymmetric response of magnetic By component to IMF between the ±E hemispheres, constricted over the terminator (about 90–93° Solar Zeniths Angle) below 300km altitude. The magnetic By component increases as the increase of the parallel IMF component in the +E hemisphere but antiparallel IMF component the –E. To detail the asymmetry, we define a new coordinate system referring to the Sun-Venus-VEX plane which is more robust in comparison with the SVE or VSO coordinate system, and develop a new data averaging method which balances the significance and resolution of data representation. Our result suggests the asymmetry is neither resulting from a large plane of current nor a line of current.

1. Introduction

Venus Express (VEX) data advance the details of the magnetic configuration near Venus, such as the asymmetry in the magnetic field draping pattern in the near magnetotail between the VSE ±E hemispheres [Zhang et al. 2010], different magnetic field topologies at low altitude [Dubinin et al. 2013], and the asymmetry of the magnetic field configuration in the low altitude ionosphere (<300 km) [Dubinin et al., 2014]. These studies used either method basing on selected cases or data averaging within equal sized bins split up from the sample space. The first method suffers from the risk of relying too heavily on interpretation to guide findings, whereas the second one yields results with inhomogeneous significance due to inhomogeneous space data coverage. In the present work, we aim to implement new statistical method to consolidate the knowledge on Venus, develop new data binning method to improve the efficiency of data representation, and tailor EOF modeling technique to build an empirical model for the low altitude magnetic configuration following He et al., [2011, 2012, 2013].

2. Figures

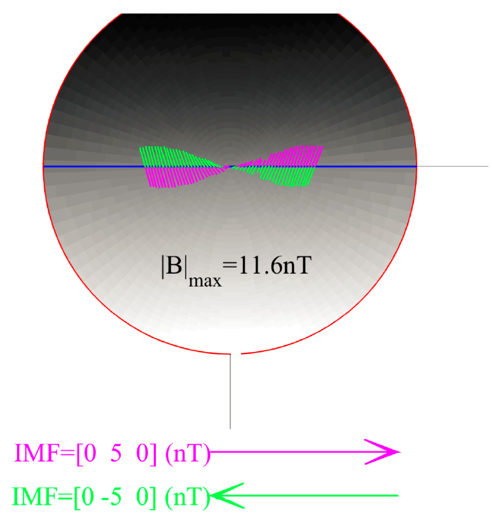

Figure 1: polar magnetic configuration represented by EOF2 in response to the reverse of IMF By component, viewed over the North Pole. The magenta elements represent IMF equals to (0, 5nT, 0) and the green ones represent for (0, -5nT, 0). In each panel, the blue line represents the terminator and the red one is the equator.

Acknowledgements

VEX magnetic data are available in the ESA's Planetary Science Archive. F10.7 index is retrieved from NASA OMNI Archive. Financial support from the Deutsche Forschungsgemeinschaft through grant DFG HE6915/1-1 and DFG VO 855/3-1 is acknowledged.

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European Planetary Science Congress 2015

Ground-based measurements of the change in the propagation period of Y-feature on Venus

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Abstract

Venus long-term observations covering one Venus year (225 days) were conducted using a ground-based telescope. The propagation periods of planetary-scale UV features were estimated for six observing periods (each observing period has 2-4 weeks) from August 2013 to June 2014. A significant periodicity of 5.2 days was detected in August 2013 while that of 3.5 days in May and June 2014. On the other hand, other observational periods, which are in a time between August 2013 and May 2014, didn't show a clear periodicity. It seems to take 8 months or less that the propagation period changes to another one. This time scale is obviously shorter than one Venus year.

1. Introduction

The dynamical mechanism of Venusian super-rotation remains a mystery for a long time. This phenomenon is that the Venus atmosphere in around 70 km cloud level moves westward at a velocity 60 times faster than the planetary rotation and wind speed reaches as fast as 100 m/s. Several theses suggest planetary-scale waves are associated with the super-rotation [e.g. 1, 2]. And also these waves are considered to form planetary scale UV features (named "Y-feature") in Venus dayside. Pioneer Venus orbiter (PVO) observed that the propagation of planetary-scale UV feature cause the periodical variation of UV brightness with the period 4-5 days [3]. They suggested that the period of brightness variation corresponds to the propagation of planetary wave and it change on a time scale of 5-10 years. Periodicity change can be argued as the vacillation of dynamical states and investigating the source of planetary waves is required to understand the super-rotation.

After the PVO mission, Venus Monitoring Camera (VMC) on-board Venus Express spacecraft provided us very beneficial images to study about long-term variation of UV features. However, the VMC captured UV features in global scale only in the southern hemisphere because Venus Express is in elliptic orbit with apocenter in the southern hemisphere. Since its orbital plane is nearly fixed in the internal frame of reference, there are some difficulties to investigate the variation of propagation periods of Y-feature in one Venus year without interruption. Therefor, the seasonal properties of Venus planetary waves are not well investigated only with spacecraft.

2. Observations and Analysis

Ground-based telescope enables us to monitor Venus with enough resolution to observe the Y-feature except near Venus conjunction seasons. Our ground-based observations were conducted at about one month intervals from mid-August 2013 to end of June 2014. Our observation covers about one Venus year (225 days) and have good potential for investigating the monthly change as compared to the Pioneer Venus observation. Used instruments are a visible multi-spectral imager (MSI) [4] with 365 nm narrowband filter (FWHM: 10 nm) installed on 1.6m Pirka telescope, constructed and operated by Planetary and Space Group in Hokkaido University.

The relative UV brightness was measured from equatorial to mid-latitudinal regions in both hemispheres based to the mean brightness of Venus disc. This analysis technique was applied for Galileo observed images, which clearly show the Y-feature, and it was confirmed that the propagation period can be derived from this analysis. When the prominent Y-feature exists and propagates with a certain period, our data show the bright and dark features having periodical and symmetrical patterns about the equator.

Brightness variation indicates the inverse relation between equatorial region and mid-latitudinal regions and the boundary of bright and dark region locates near the latitudes of 30° N and 30° S. The periodicity of the propagation of the Y-feature is studied from our relative brightness data using Lomb-Scargle periodgram [5]. UV images from VMC (narrowband channel centered at 365 nm) are also used to compare with our data and investing the periodicity.

3. Results and Discussions

From results of our ground-based observation (shown in Table 1), it was revealed that the periodicity in the UV brightness variation changes with in a Venus year (225 Earth days). In August 2013, we detected ~5.2 days periodical brightness change in equatorial and both in northern and southern mid-latitudinal regions. The retrieved periodical and symmetric bright and dark pattern suggests the existence of prominent Y-feature in this observation period. In contrast, after the mid-September 2013, there was no prominent and periodical brightness variation in the most of the observation period. The absence of the periodical variation was also confirmed in February 2014. However, our last two observational periods showed ~3.5 days periodical variation again. Since estimated periods of sinusoidal variations are same in May and June 2014 and their phases are consistent, 3.5 days period is considered to last for about two months. It is pointed out from our study that the possibility of the change of dynamical states occurs in one Venus year. The exact time scale of this change is under investigation, and our further observation has started from April 2015.

Table 1: List of periods of analysis with 90% significance or more. In three out of six observing periods, we can find clear periodicity (~5.2 and ~3.4 days) in UV brightness variation.

	Observing period	Period [days]
# 1	Aug 19 – Aug 29, 2013	5.15
# 2	Sep 23 – Oct 8, 2013	-
# 3	Oct 18 – Dec 8, 2013	-
	Jan 11, 2014: Interior Conjunction	
# 4	Feb 25 – Mar 28, 2014	-
# 5	May 6 – June 1, 2014	3.49
# 6	Jun 19 – Jun 30, 2014	3.49

Acknowledgements

The author deeply appreciates to Mr. Yasuo Sano and all other staffs of Nayoro observatory for their kind help for observation.

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Long-term Variation of Temperature and Dynamic at the Morning Terminator in Venus Upper Atmosphere from Ground-Based Infrared Heterodyne Spectroscopy

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Abstract

We report on temperatures and wind velocities at the morning terminator in the Venusian upper mesosphere/lower thermosphere, deduced from analyzing very high resolution infrared spectroscopic data of CO_2 emission lines acquired between 1990 and 2013.

1. Introduction

The dynamics of the transition zone between the region dominated by sub-solar to anti-solar (SS-AS) flow above 120 km and the superrotation dominated region below 90 km is not yet fully understood. Temperatures in the same region are not very well constrained either. Measurements are essential to gain a global understanding of the atmosphere and to validate global circulation models. Space based observations can only partially provide temperatures and do not offer direct wind measurements at these altitudes [1,2,3 & 4]. Ground-based results still lack in time coverage and spatial resolution. Hence measurements on various time scales and different locations with sufficient spatial resolution on the planet are important. Such observations are carried out with the infrared heterodyne spectrometers THIS from University of Cologne, HIPWAC and IRHS from NASA Goddard space flight center.

2. Instrument and Technique

Infrared heterodyne spectrometers provide a high spectral resolution ($R>10^7$). In addition compared to mm and sub-mm observations a high spatial resolution on the planet is guaranteed. The Instruments can be operated between 7 and 13 μm [5]. Temperatures and winds in planetary atmospheres are retrieved from detection of narrow non-LTE emission lines of CO_2 at 10 μm. These emission lines are induced by solar radiation and occur only in a narrow pressure/altitude region around 110km [6]. Resolving this single molecular feature allows retrieval of temperatures and wind velocities. Wind velocities can be determined from the Doppler-shifts of the emission lines with a precision of 10m/s. Temperatures with a precision up to 5K can be calculated from the Doppler-width of the emission lines.

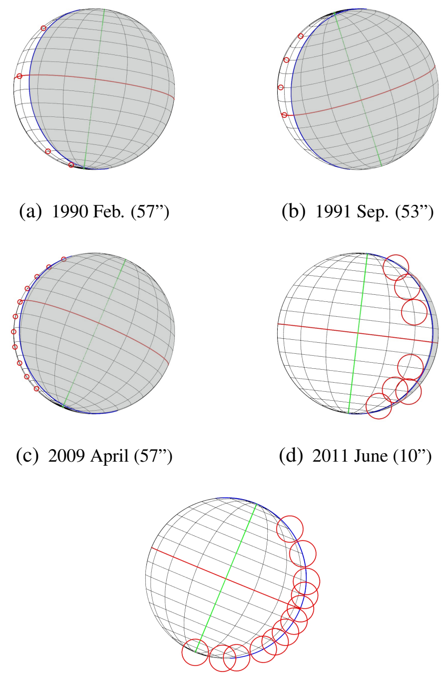
3. Observations and Results

During the last decades several observing runs were dedicated to collect day-side information from the Venusian upper atmosphere. These observing runs delivered comprehensive data sets to investigate long term temporal variability. In this presentation we will focus on mesurements at or close to the morning terminator (Figure 1). Table 1 gives an overview of relavant observational conditions of the different campaigns. In all cases the distance from the terminator is smaller than 2h.

Table 1: Overview of gathered data

date	illu.[%]	size["]	Fov ["]	data[1]
1990 Feb.	11	53	0.9	W,T
1991 Sept.	8	53	0.9	W,T
2009 April	3	60	1.6	W,T
2011 June	96	10	1.6	W,T
2013 March	100	10	1.6	W,T

[1] W: wind data received, T: temperature data received



(a) 1990 Feb. (57”) (b) 1991 Sep. (53”)

(c) 2009 April (57”) (d) 2011 June (10”)

(e) 2013 March (10”)

Figure 1: Observing geometries for campaigns at and close to the MORNING TERMINATOR of Venus. Equator (red), Terminator (blue) and the Central Meridian Longitude (green) are indicated. Each observing geometry includes a red circle indicating the relative size of the telescope beam on the planet. The number behind the date gives the apparent diameter of Venus in arcseconds.

As an example Figure 2 shows the temperatures at the morning terminator of all campaigns. Temperatures in the range of 150-240 K are observed. We will present in detail the long-term behavior of the temperatures and give a comparison to temperatures at the evening terminator. In addition the line-of-sight wind velocities were investigated. For comparison of different observing geometries it is necessary to correct the measurements to the extended beam on the planet. Here we also present a detailed study of the long-term behavior of this extended beam corrected wind values. Furthermore we will also compare the wind values of the morning termintor to the evening terminator.

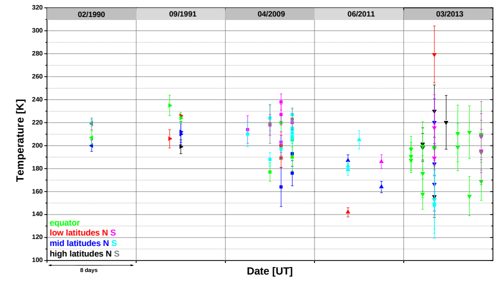


Figure 2: Temperatures at the morning terminator from different observations between 1990 and 2013

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Thermal Structure of Venus' Dayside in 110 km Altitude Based on Ground-Based Heterodyne Observations Between 2007 and 2014

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Abstract

We present an extensive comparison of temperature measurements of Venus' upper atmosphere between 2007 and 2014. The data are acquired by analyzing non-LTE CO_2 emission lines which are recorded by ground-based observations at 10 µm. The results show features of the thermal structure of the Venusian atmosphere in 110 km altitude which can be useful to improve modelling attempts in this altitude region. The measurements provide a large quantity of data points mapping a good part of the dayside of Venus.

1. Introduction

The structure of Venus atmosphere has been the target of intense studies in the past decade. The recent space mission Venus Express (VEX) has shed light on many open questions concerning the thermal and the dynamical behavior of its atmosphere. As to the imminent shut down of the spacecraft and no notion of near future space missions to Venus, the importance of ground-based observations increases significantly.

We use Doppler shifted non-LTE emission lines of CO_2 at 10 µm to obtain wind velocities and temperatures in Venus' atmosphere at 110 km altitude [1]. These emission lines arise only from insolation hence our measurements are bound to the dayside of Venus. To facilitate observations of these lines from the ground, we use heterodyne spectroscopy which is an eminent technique to provide reasonable high resolution ($R \propto 10^7$) [2].

2. Technique and Instrumentation

Generally heterodyning is the superposition of a local oscillator (LO) with the singal coming from the sky, resulting in one signal in a down converted frequency regime. Since it provides ultra high resolution ($R \propto 10^7$) it is possible to fully resolve the observed CO_2 emission lines. Additionally heterodyning in the infrared regime provides good spatial resolution which enables us to resolve the planet and observe different positions on the apparent disk of Venus.

The data presented here were recorded by the instruments THIS (Tuneable Heterodyne Infrared Spectrometer) built in Cologne, Germany [3] and HIPWAC (Heterodyne Instrument for Planetary Wind and Composition) which is the transportable follower of the first infrared heterodyne spectrometer (IHRS) developed at the NASA Goddard Space Flight Center [4,5].

3. The Campaigns

We present results of temperature measurements from nine observing campaigns between 2007 and 2014. The data were acquired at the McMath-Pierce solar telescope at Kitt Peak National Observatory, Arizona and the NASA Infrared Telescope Facility on Mauna Kea, Hawaii. During the campaigns the apparent diameter and illumination of Venus varied between 22" and 57" and 3% and 55%, respectively. Tab. 1 gives an overview of the important observational parameters for the different campaigns and Fig. 1 shows the corresponding observing geometries.

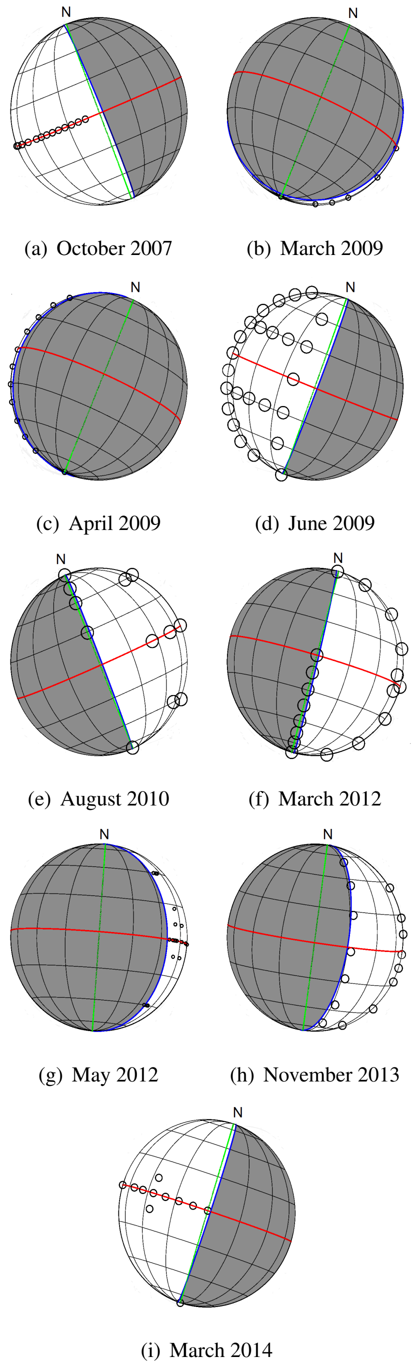

Figure 1: Observing geometries for the different campaigns indicating the equator (red), the terminator (blue) and the central meridional longitude (green). The black circles indicate the diffraction limited field of view in real scale to the diameter of Venus' apparent disk.

date	illu.[%]	size["]	Fov ["]	Instr.
Oct.2007	47	25	0.9	THIS
Mar.2009	4	57	1.6	THIS
Apr.2009	3	57	1.6	THIS
Jun.2009	50	24	1.6	THIS
Aug.2010	55	22	1.6	THIS
Mar.2012	21	23	1.6	THIS
May.2012	7	51	0.9	HIPWAC
Nov.213	33	35	1.6	THIS
Mar.2014	52	23	0.9	HIPWAC

Table 1: Important observational parameters for the different campaigns.

4. The Results

The observations yield a large quantity of temperature measurements at different positions on the planetary disk which enables us to map a good part of the dayside of Venus. Several plots will give insight into the thermal structure of Venus in 110 km altitude during the different campaigns. In Addition an extensive comparison yields a general impression of the behavior of the temperatures in Venus upper atmosphere which can be useful to improve modelling attempts.
Ongoing analysis of thermal variabilities is in progress and might add to the results which will be presented at the conference.

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Thermal structure and minor species of Venus mesosphere by ALMA submm ground-based observations

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Abstract

Submillimeter observations obtained with the Atacama Large Millimeter Array (ALMA) offer the possibility to monitor the temporal evolution of sulfur species and water in the upper atmosphere of Venus. Here, we report on the first ALMA retrievals of CO temperatures, HDO, SO, and SO_2 obtained over the entire disk of Venus on November 14, 2011.

1. Introduction

Venus upper atmosphere (70 – 150 km altitude) is one of the most intriguing regions on the planet. It corresponds to a transition region characterized by a complex dynamics and circulation: strong retrograde zonal winds dominate the lower mesosphere while a solar-to-antisolar circulation driven by a day-to-night temperature gradient can be observed in the upper mesosphere/lower thermosphere [1]. In addition, photochemical processes play an important role at these altitudes and affect the thermal structure and chemical stability of the entire atmosphere [2,3]. Sulfur dioxide and water vapor are key species in the photochemical cycles taking place in the troposphere and mesosphere of Venus [4, 5]. Both molecules are abundant in the lower troposphere (150 ppm and 30 ppm respectively [6,7]). They are carried by convective transport, together with the Hadley circulation, up to about 60 km where SO_2 is photodissociated and oxydated, leading to the formation of H_2SO_4 which condenses in the clouds enshrouding the planet. Previous observations obtained by several instruments on board Venus Express and during ground-based campaigns have shown evidence of strong temporal variations, both on day-to-day as well as longer timescales, of density, temperature and SO_2 abundance [2,8,9]. Such strong variability, especially near the terminators, is still not well understood.

2. ALMA observations

Ground-based observing campaigns of Venus were organized in support of space exploration observations since the early stage of Venus Express operations in 2006 [2,3,10]. Earth-based observations provide complementary information to spacecraft data by allowing a complete view of the planetary disk at a given time and a long-term coverage, which is of particular interest in view of the official end of Venus Express operations in January 2015.

The Atacama Large Millimeter Array (ALMA) offers a unique opportunity of probing Venus' upper mesosphere (60 – 120 km) and of monitoring minor species, winds and the thermal structure. A first set of observations was obtained in November 2011 during the first ALMA Early Science observation cycle [11,12]. These observations targeted SO_2, SO, HDO and CO transitions around 345 GHz during four sequences of 30 minutes each. The Venus' disk was about 11" with an illumination factor of 90%, so that mostly the dayside of the planet was mapped.

In a preliminary study, [11] analyzed the ALMA observations acquired on November 14 and 15, 2011. Assuming a nominal dayside CO abundance profile from [13], the CO line at the disk center was used to retrieve a vertical temperature profile, later used to derive the abundances of minor species averaged over the disk. Maps of SO and HDO acquired on Nov. 14, 2011 show significant local variations over the disk, with an enhancement in the northern hemisphere towards the evening terminator (**Fig.1**).

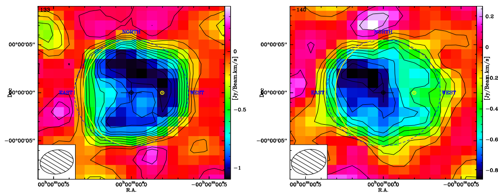

Figure 1: Maps of: (Left) the SO line depth at 346.528 GHz on Venus, and (Right) HDO at 335.395 GHz, recorded on November 14, 2011. The planet size is 11″; the FOV is 1.2 × 2.4″. The evening terminator is indicated by the yellow line (From [11]).

Spectra of SO and SO_2, integrated over the disk, are consistent with mean mixing ratios of 4 ppb and 6 – 7 ppb respectively, above an altitude of 85 km. The HDO spectrum integrated over the disk is best fitted with a H_2O mixing ratio of 1 to 1.5 ppm, assuming a D/H enrichment of 200 in the Venus mesosphere. These results are consistent with previous single dish submillimeter measurements [14,15,2]. In addition, the high resolution CO map obtained during ALMA Cycle 0 was used to infer mesospheric wind field [12]. The upper mesospheric winds are consistent with a dominant subsolar-antisolar circulation.

3. CO thermal structure

Assuming nominal night-time and dayside CO abundance profiles from [13], we retrieved vertical temperature profiles over the entire disk as a function of latitude and local time for the first day of observation on Nov. 14, 2011 (**Fig. 2**).

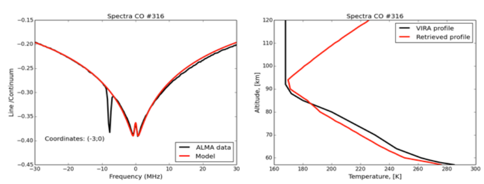

Figure 2: (Left) ALMA spectrum of CO with continuum subtracted (black line) compared to model spectrum (red line). (Right) Temperature profile inferred from the inversion of the CO spectrum (red line) compared to VIRA profile.

4. Mapping of Water and sulfur species

We plan to use the retrieved temperature profiles to derive the abundances of minor species (HDO, SO, SO_2) in each pixel of the disk for the first day of observation in order to study their variability with latitude and local time. In a further step, we will extend our analysis to the four days of observation.

Acknowledgements

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Tidal constraints on the interior of Venus

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Abstract

As a prospective study for a future exploration of Venus, we propose to systematically investigate the signature of the internal structure in the gravity field and the rotation state of Venus, through the determination of the moment of inertia and the tidal Love number.

1. Context

Although Venus is very similar in size and mass to the Earth (and therefore often referred to as its twin sister), their internal structures might differ in several ways. Indeed, the lack of plate tectonics as means to expel heat probably leads to a hotter interior for Venus. As a consequence, Venus's core should be at least partially, and maybe entirely, molten. The determination of the tidal Love number k_2 from Magellan data by [1] seems indeed to confirm the presence of a fluid core. However, there is little to constrain the core mass : Cosmochemical models ([2]) suggest core mass fractions between 23.6 and 32.0% implying a mantle mass proportionately similar to or greater than Earth's. The Venera landers returned a number of K, U and Th measurements that imply bulk ratios, and hence internal radiogenic heating rates, comparable with Earth. As the moment of inertia of the planet is not known, the first order internal structure depicted for Venus is often just a scaled version of the Earth's one. In addition, the Venus Express Mission measured a variation in the venusian length-of-day [3] that could bring information on the interior. However, the rotational models were not able to explain this large variations [4].

2. Mantle composition and core state

We test various mantle compositions, core size and density as well as temperature profiles representative of different scenarios for formation and evolution of Venus. The mantle density ρ and seismic v_P and v_S wavespeeds are computed in a consistent manner from given temperature and composition using the Perple_X program [5]. This method computes phase equilibria and uses the thermodynamics of mantle minerals developped by [6].

3. Computation of tidal deformation

The viscoelastic deformation of the planet interior under the action of periodic tidal forces are computed following the method of [7]. The Poisson equation and the equation of motions are solved for small perturbations in the frequency domain using a compressible viscoelastic rheology. The Love number k_2 and the dissipation function, Q^{-1} are computed by integrating the radial functions associated with the radial and tangential displacements, the radial and tangential stresses, and the gravitational potential, as defined by [8]. The deformation of the liquid core is assumed to be static, and the simplified formulation of [9] is thus employed.

4. Love number and moment of inertia

For a variety of interior models of Venus, the Love number, k_2, and moment of inertia factor, I/MR^2, will be computed following the method described above. The objective is to determine the sensitivity of these synthetic results to the internal structure. These synthetic data will be used to infer the measurement accuracies required on the time-varying gravitational field and the rotation state (precession rate, nutation and length of day variations) to provide useful constraints on the internal structure.

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EPSC Abstracts
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Search for ongoing volcanic activity on Venus

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Abstract

We report results of systematical analysis of the whole data-set obtained by the Venus Monitoring Camera (VMC) on-board the Venus Express (VEx) spacecraft at the night side of the planet. In this data-set we searched for transient bright events which exhibit behaviour of a hot spot on the surface.

1. VMC data

VMC was designed to perform observations of the surface through 1-μm transparency "window" at the night side [1], when the spacecraft is inside of the planet' shadow. Observations were made in close to nadir geometry, and due to this the camera was able to image a given place from 3 – 5 consequent orbits before it goes out of the camera field of view. The next observational session of the same place was possible after ≈ 100 days, when the orbital configuration becomes similar.

In this mode VMC has observed equatorial regions and significant part of the northern hemisphere up to latitudes of ≈ 50°N.

2. Transient bright events

Active volcanic events, either lava or hot gas releases, have to manifest themselves via local increases of near infra-red (NIR) flux from the surface. These bright spots can be detected by the VMC [2]. However, it is impossible to distinguish occasional bright spots caused by volcanic phenomena from those caused by differences in the atmosphere opacity [3].

Only events that are observed from several orbits at the same places might be related to volcanic activity [3, 4].

From VMC observations and modelling it is possible to estimate the total flux from the bright spot, and possible combinations of hot spot size and temperature.

Such detection was made at the edges of the Ganiki Chasma rift zone, where four such events have been found, and the question of presence or absence of similar events in the other parts of Venus is of exceptional interest.

3. Conclusions

A systematic search is being undertaken by comparing all orbital mosaics automatically. The results obtained will allow us to understand whether the previously detected event was unique, or whether there are other examples that permit us to develop a more robust estimate of the range of currently active volcanism and whether one can estimate present rate of volcanic activity on Venus.

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Ground and space based cloud-top wind velocities using CFHT/ESPaDOnS (Doppler velocimetry) and VEx/VIRTIS (cloud tracking) coordinated measurements

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Abstract

We will 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. Our aim is contribute to the characterisation of the zonal and meridional wind latitudinal profiles on hour and day-timescales. This will be done by tracking Doppler shift of solar and CO_2 lines over the dayside hemisphere in coordination with ESA's Venus Express orbiter. Our observations measured winds at cloud tops at latitudes 60°S-60°N, while Vex/VIRTIS privileged southern latitudes poleward of 45°S. This coordination effort intended to provide a combined monitoring of short-term changes of wind amplitude and directions with extensive spatial coverage.

We present results based on inter comparison of ground-based Doppler velocimetry of cloud-top winds and cloud tracking measurements from the Venus Express spacecraft. Doppler wind velocimetry obtained with the 3.60 m Canada-France-Hawaii telescope (CFHT) and the Visible Spectrograph ESPaDOnS in February 2011 consisted of high-resolution spectra of Fraunhofer lines in the visible range (0.37-1.05 μm) to measure the wind velocity using the Doppler shift of solar radiation scattered by cloud top particles in the observer's direction. The complete optical spectrum was collected at a phase angle $\Phi = (76 \pm 0.3)^\circ$, at a resolution of about 80000.

Both ground-based and Venus Express measurements show considerable day-to-day variability revealing wave propagation and angular momentum transport in latitude which needs to be carefully assessed. ESPaDOnS and the sequential technique of visible Doppler velocimetry has proven a reference technique to measure instantaneous winds. These measurements are necessary to help validating Global Circulation Models (GCMs) [2], to extend the temporal coverage of available datasets. The ground-based observations in the base of this project are critical in their complementarity with Venus Express, which was recently decommissioned.

We compared our measurements with simultaneous observations using the Visible and Infrared Thermal Imaging Spectrometer (VIRTIS) instrument from the VEx orbiter. CFHT observations included various points of the dayside hemisphere, between $+60^\circ$N and 60°S, by steps of 10°, and from sub-Earth longitude $[\phi - \phi_E] = 0^\circ$ to -50° corresponding to 7:30a - 10:50a, while VIRTIS-M UV (0.38 μm) cloud tracking measurements extended on the dayside south hemisphere between 30 and 50°S and 9:05a - 10:50a.

Our analysis technique allows an unambiguous characterisation of the zonal wind latitudinal, local time profile and its temporal variability. We will also present a latitudinal profile of the meridional wind in the mid-latitudes range.

1. Introduction

In the Venus' lower mesosphere (65?85 km), visible observations of Doppler shifts in solar Fraunhofer lines have provided the only Doppler wind measurements near the cloud tops in recent years [4, 5, 7, 8]. The region is important as it constrains the global mesospheric circulation in which zonal winds generally decrease with height while thermospheric SSAS winds increase [1,6]. Renewed interest in measuring the winds at clouds top from the ground has emerged in the course of the Venus Express mission. On Venus Express, atmospheric circulation at 70 km (and as well near 50 km) is being measured from cloud tracking by both VIRTIS-M and VMC instruments [1,3]. However, winds derived in this manner are usually averaged over several days of observations and do not reflect instantaneous wind velocity and its significant variability at shorter time scales. In addition, cloud tracking is not able to measure wind fields above cloud level, where wind inferences have to rely on indirect hypothesis such as cyclostrophic balance. The main purpose of this study is therefore to provide direct and instantaneous wind velocity measurements using visible Fraunhofer lines scattered by Venus cloud tops.

2. Method

With ESPaDOnS, the complete optical spectrum, from 370 to 1050 nm, is collected over 40 spectral orders in a single exposure at a resolution of about 80,000. Our choice of observing dates offers the best compromise between observability at Mauna Kea and the need to (i) maximize the angular diameter of Venus and spatial resolution on the disk, and (ii) minimize Venus phase angle and illuminated fraction as only the dayside hemisphere is observed

In the single scattering approximation, the Doppler shift measured in solar light scattered on Venus dayside is the result of two instantaneous motions: (1) a motion between the Sun and Venus upper clouds particles, which scatter incoming radiation in all directions including the observer's ; this Doppler velocity is minimal near Venus sub-solar point; (2) a motion between the observer and Venus clouds, resulting from the topocentric velocity of Venus cloud particles in the observer's frame; this effect is minimal near Venus sub-terrestrial point. The measured Doppler shift is the sum of those two terms. It therefore varies with planetocentric longitude. The Doppler shift vanishes at the half phase angle meridian, where both terms cancel each other [5] and we use this meridian as "zero-Doppler-reference" to check for instrumental or calibration drifts. The Doppler velocities are modelled using two kinematical templates for the zonal wind: (1) solid rotation with v zonal = v (equator) $\times$ cos (latitude), (2) uniform retrograde velocity, v zonal = v (equator). Both models are explored within latitudinal range 60S-60N. Once the best fit is obtained, we define the acceptable domain at 2-sigma and also test alternative models, including the combination of both zonal and meridional circulations.

Venus Express cloud top wind indirect measurements based on tracking using images taken with the VIRTIS instrument [1] indicate nearly constant zonal winds in the Southern hemisphere between 0 and 55 deg S, with westward zonal velocities of 105 m/s at cloud tops near 70 km, with detection of a meridional, poleward component with a peak velocity of 10 $\pm$ 10 m/s. However, variability of the zonal velocity is significant over an hour timescale, at all longitudes, rapid changes that are detectable with the Doppler technique, but not with the cloud-tracking used by Venus Express. In CFHT/ESPaDOnS measurements of Feb. 2011, during discretionary run 11AD98, velocity variations at $[\phi - \phi_E] = 0°$ and 30° lat near morning terminator are reported with an amplitude of $\pm$ 18.5 m s^{-1} relative to the mean (day-averaged) Doppler zonal velocity v = 117.5 m s^{-1}, over a period of about 2 hours, revealing local wave activity [5].

We will present the results of our tracking on the short-timescale (daily) changes in the meridional profile of the zonal wind, confirm the detection of the meridional wind and constrain the extent of the Hadley cell, and constrain the presence of a sub-solar to anti-solar thermospheric component near the cloud top layers.

Acknowledgements

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EPSC Abstracts
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The vertical density profile of the mesosphere of Venus by independent measurements from SPICAV/SOIR and aureole photometry

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Abstract

The mesosphere of Venus, above the optically thick cloud deck, remains poorly known and shows an important variability as a function of position and time as revealed by Venus Express (VEx) data (SPICAV/SOIR experiment). For the first time, we validate the SOIR vertical density profile by reproducing the accurate photometry of the aureole of Venus obtained by the HMI instrument onboard SDO, during the solar transit of Venus on June 5-6, 2012. The aureole is produced by sunlight refraction in the mesosphere, and is highly sensitive to the details of the vertical density variations. For this task, we use the data that SOIR has captured from the Venus Express orbiter at the time Venus transited the Sun. The photometry of the aureole at the same latitude is then fitted by a multi-layer model adopting the vertical profile of SOIR. We find that our fit is sensitive to the variations of the CO_2 mixing ratio, the altitude of the opaque layer at visible wavelengths, and the scale height of the aerosols above them. In particular, we determine the last two parameters. As the inversion method has been validated, we will invert the photometric light curve at all other latitudes observed on the evening limb.

1. Introduction

The transit of Venus in June 2012 provided a unique case study of the Venus' atmosphere transiting in front of the Sun, while at the same time ESA's Venus Express orbiter observed the evening terminator at solar ingress and solar egress. Close to ingress and egress phases, we have shown that the aureole photometry reflects the local density scale height and the altitude of the refracting layer [1].

2. SDO Observations

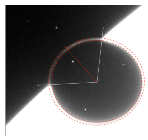

Figure 1 : Ring photometry performed on NASA's Solar Dynamics Observatory of the LWS program. The HMI instrument (Helioseismic Magnetic Imager) observes the full solar disk at 6173 Å with a 1 arc-sec resolution and was used to image the aureole on June 5-6, 2012.

3. SPICAV/SOIR Observations

SOIR [2] performs solar occultation observations of the Venus atmosphere from the VEX spacecraft, which is in a polar orbit with its periapsis located above the North Pole. The vertical size of the instantaneously scanned atmosphere at the limb tangent point varies from a few hundreds of meters for the Northern measurements to tens of kilometers for the Southern measurements. The altitude range probed by SOIR, i.e., where measurements are scientifically mean- ingful, varies from 70 km up to 170 km. The lower boundary corresponds to total absorption of sunlight by Venus' clouds, and the upper boundary to the detection of the strongest CO_2 band in the selected SOIR wave number range. The continuum of absorption in the SOIR spectra is primarily shaped by the extinction caused by the aerosol particles present in the upper haze (between ~70 and 100 km) of the Venus mesosphere.

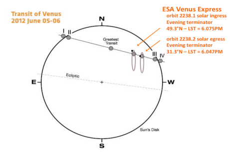

Figure 2 : Geometry of the VEx/SOIR vertical temperature profiles obtained during orbit 2238 at terminator during solar ingress (49.3N - LST = 6.075PM) and egress (31.3N - LST = 6.047PM) as seen from the orbiter. Solar occultations take place at 6:00a and 6:00p local time on Venus, at the same local time probed by the transit aureole.

4. Model

A new ray-tracing transmission-refraction model has been developed to fit the transit data based on a stellar occultation point-source geometry. The main problem in the case of Venus was the limb surface of the Sun, the star representing an extended light source through the upper mesosphere. So, the model is based on an occultation code [3, 4] modified to take into account the extended source and inverse with a MCMC Markov Chain Monte Carlo algorithm to find the best parameters for the altitude of the opaque aerosol layer in tangent geometry at visible wavelengths, and the scale height of the refracting atmosphere layers above.

Fig.3 indicated that simultaneous SOIR data obtained at evening terminator at 49.3°N on June 6, 2012, when inserted in the model without modification, the fit produced is in good agreement with the photometry extracted for the SDO imaging at 617.3 nm.

5. Conclusion

SDO/HMI measurements are in agreement with the VEx/SOIR temperatures obtained during orbit 2238 at evening terminator during solar ingress (49.3°N - LST = 6.075PM) and solar egress (31.3°N - LST = 6.047PM) captured from the Venus Express orbiter at the time Venus transited the Sun. As the inversion method has been validated, we will invert the photometric light curve at all other latitudes observed on the evening limb

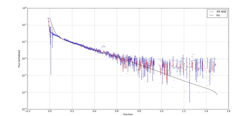

Figure 3 : Representation of the refraction aureole flux in in the SDO imaging at 617.3 nm selected at the latitude of simultaneous VEx/SOIR vertical temperature profiles obtained during orbit 2238 at 49.3N. Maximum intensity for the aureole is obtained near second contact (fraction = 0.0). The red curve with the blue error bars is the measured flux. The black curve is the model of aureole intensity obtained with the VEx/SOIR data.

Acknowledgements

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Craters and coronae – the influence of volcano-tectonic features on impact crater formation on Venus

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Abstract

This study takes a more detailed look on the types of Venusian tectonic structures affecting polygonal impact crater formation and shows that the surroundings of the Venusian volcano-tectonic features do not actually favour the formation of polygonal impact craters compared to the circular craters. However, the pre-existing structures in the target, caused by volcano-tectonic features, clearly control the orientation of PIC rims when PICs form near these features. As PICs reveal older tectonic features below the surface, this study provide further insight into the tectonic history of Venus and PIC formation.

1. Introduction

Impact craters on Venus, just like on other planets and smaller bodies in the solar system, sometimes display a distinctly polygonal shape rather than being circular or elliptical in plan view [1–8]. Such PICs (polygonal impact craters) are thought to be formed when the dominating heterogeneities in the target, for example faults and fractures, control the formation of craters [3–8]. Thus, also the orientations of the straight crater rim segments are non-random; in many cases the straight rim segments have statistically significant positive correlations with the orientations of various tectonic structures [2].

Earlier [1–2], we established the presence of 121 PICs in the Venusian impact crater population >12 km in diameter. Most of these PICs are shown to be parallel with the structural orientations of the tessera terrain, the rift zones or the concentric components of volcano-tectonic features [2]. We also noticed that in the cases where PICs are located near the volcano-tectonic features, like coronae, the volcano-tectonic features are mostly rather large in diameter, their annuli are clearly visible in topography, and many of them show evidence of a complex, multi-phase formation process [9].

In our on-going study, we are taking a more detailed look on the types of Venusian tectonic structures affecting PIC formation. Some of our key questions are how these effects vary with the type, size, and location of the tectonic structure with respect to the PICs. The study was carried out by using the Magellan SAR (Synthetic Aperture Radar) images (75 m/px), which cover 98% of the surface [10], with additional insight provided by Magellan topographic data (~4640 m/px).

2. Results and discussion

According to our studies, it seems that the surroundings of the volcano-tectonic features do not avour the formation of the polygonal impact craters compared to the circular craters (Figure 1). Approximately 34% of Venusian circular craters and ~31 % of PICs >12 km in diameter are located less than ten crater diameters from the outer edge of the corona-like feature annulus. Correspondingly, ~7% of circular craters and 7% of PICs are situated less than two crater diameters from the corona. However, in the case of PICs which are located close to the coronae or corona-like features, the straight crater rim segments of PICs are usually oriented with the structural orientations of the concentric components of the coronae [2]. In other words, even though the coronae or volcano-tectonic features do not offer exceptionally favourable conditions for PIC formation, in the cases where PICs are formed near the coronae, the most probable reason for the orientation of the straight rim segments are the pre-existing structural conditions caused by the nearby volcano-tectonic feature.

The complex and problematic nature of the PIC formation process is emphasized by the observation that there are also circular craters in the vicinity of a corona–PIC pair. There can be, however, several possible explanations for the different morphologic appearance of the craters. Firstly, the surroundings of the volcano-tectonic features most probably are not homogeneous. This is supported by the fact that in most of the observed cases the PICs and the circular craters appear to be located quite far from each other. Also, there may be notable differences in cratering processes or age and size of the craters. These questions will be studied in greater detail in the future, which may help to clarify the conditions which favour the formation of PICs.

Another interesting topic of the future work will be the study of the PICs which do not show any correlations with the visible tectonics, or which are located a relatively featureless surface, like on plains. According to our assumption, these PICs can be utilised to evaluate the orientation of hidden tectonic structures under the lava plains, which would provide further insight into the tectonic history of Venus and PIC formation.

3. Conclusions

The surroundings of the volcano-tectonic features do not seem to be more favourable for the formation of the polygonal impact craters compared to the circular craters – actually both types of craters are equally common in their vicinity. However, when PICs are formed near coronae or other volcano-tectonic features, the dominating fractures of the target material caused by this feature control the orientations of PIC rims.

Acknowledgements

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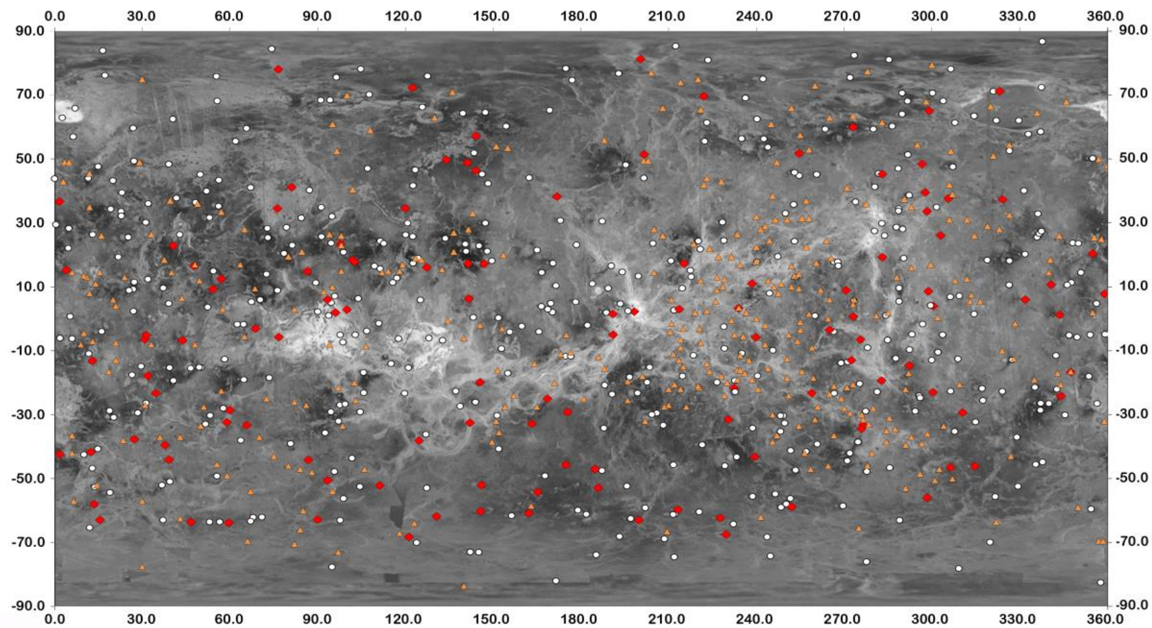

Figure 1: The distribution of Venusian coronae (orange triangles) with circular (white dots) and polygonal (red diamonds) impact craters (D>12 km) plotted on Magellan data. Approximately 34% of Venusian circular craters and ~31 % of PICs (D>12 km) are located less than ten crater diameters from a corona-like feature so the coronae do not seem to be more favorable for the formation of the PICs compared to the circular craters.

EPSC Abstracts
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Improved Knowledge of Venus Atmospheric Structure

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Abstract

Experiments onboard the European Space Agency's Venus Express orbiter has extended our knowledge about the vertical temperature and density structure above the clouds. The observations have been obtained by different techniques at different local times and latitudes and with different vertical and horizontal resolutions and coverage.

1. Introduction

Atmospheric structure of Venus has been measured from Venera and Pioneer Venus entry probes, inferred from radio occultation method from Mariner 5 and 10 fly-by spacecraft, Venera 9-16 missions as well as Pioneer Venus, Magellan and Venus Express orbiters and retrieved from infrared, solar and ultra-violet stellar occultations from Venus Express orbiter, derived from infrared observations from Pioneer Venus and Venus Express orbiters and sampled from atmospheric drag on Pioneer Venus, Magellan and Venus Express orbiters. The numerous new results from ground-based and spacecraft observations refine our knowledge of the Venus atmospheric structure from the different experiments using different techniques.

2. Experiments Considered

In this study we considered ground-based measurements obtained recently from infrared and sub-mm experiments as well as the results of five experiments on Venus Express orbiter (**Table 1**).

Table 1. Venus Express Experiments

Experiment	Remarks
SOIR	Vertical profiles of CO_2 abundance and atmospheric temperature derived from solar occultation from CO_2 number density as well as molecular rotational temperatures from CO_2 spectral structure [1]
SPICAV	Stellar occultations allow determination of CO_2 density and temperature vertical profiles[2]
VeRa	Vertical profiles of temperature, pressure and neutral number density [3]
VIRTIS-M VIRTIS-H	Medium spectral resolution maps and High spectral resolution nadir observations [4, 5]
VIRTIS-H	Limb observations of airglow [6]
VEXADE	Atmospheric Drag Experiment using spacecraft solar panels near periapsis

Ground-based results include:

- Thermospheric temperature structure profiles [7, 8, 9]
- Transit of Venus [10]

Since the different experiments use different techniques and have different horizontal and vertical resolutions and starting assumptions, we examined the inherent measurement errors and the variability of the respective data.

Some experiments on Venus Express have multiple modes which need different methods to infer temperature or density information as a function of altitude. Further, in some case different groups have used different approaches or assumptions to analyse the same observations. Thus, it was natural to compare the results from different experiments and compare them. However, in most cases the altitude and horizontal coverage from the different experiments is different and often obtained at different times. Hence results from each experiment were binned in latitude and altitude or pressure levels and averaged to enable a comparison of the averaged results. This inter comparison is the first step in updating the Venus International Reference Atmosphere (VIRA) model adopted through COSPAR [11].

3. Main Results

The atmospheric structure knowledge has been improved from recent ground-based and spacecraft observations from cloud tops to about 200 km. Below the cloud tops no new measurements have been obtained since the VeGa balloons and the VeGa 2 lander. All experiments present a consistent picture of the thermal structure which agrees with the warming of the atmosphere by the absorption of incident solar energy in the cloud-haze layer, however, inversion layers are found in the 90-140 km region which are local time dependent. The presence of these warmer and cooler layers may be due to large scale dynamics as well as due to presence of ozone discovered by Venus Express in the thermosphere.

A greater variability in atmospheric density is observed in the 90-130km region from SOIR and SPICAV results, but the validity of such variability is as yet uncertain as it is not seen in the VeRa results or in the atmospheric drag results.

4. Summary and Conclusions

An international team formed under the auspices of International Space Science Institute (ISSI) has considered the post VIRA observations and compared the results from different experiments on Venus Express orbiter. News aspects of thermal structure have been discovered – presence of a very cold region from SOIR and SPICAV observations, presence of inversion layers – alternating warm and cooler layers above 95 km, substantial local time variations above 90 km among the significant findings. VeRa profiles show presence of small scale gravity waves. Thermal tide signatures are also present in most data but the team did not have adequate resources to look into details of the large and small scale waves.

Acknowledgements

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EPSC Abstracts
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Studying the Venus terminator thermal structure observed by SOIR/VEx with a 1D radiative transfer model

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Abstract

The SOIR instrument on board Venus Express routinely measures the CO_2 number density profiles in the mesosphere and thermosphere region at the Venus terminator using the solar occultation technique. Assuming the hydrostatic equilibrium, we derive temperature profiles, which show a permanent cold layer at 125 km, surrounded by two warmer layers at 100 km and 140 km. We developed a 1D conductive radiative transfer model to study the mean SOIR thermal profile, considering the main species, and carefully modelling the radiative terms. In order to correctly reproduce the thermal profile, aerosols cooling and heating terms are added. We describe how aerosols number density profiles can be calculated to have a good match of the thermal profiles.

1. Introduction

SOIR is an infrared spectrometer that probes the Venus terminator region since 2006. The measurements are taken on the morning and evening sides of the terminator, covering all latitudes from the North Pole to the South Pole. The covered wavelength range - 2.2 to 4.3 µm - allows a detailed chemical inventory of the Venus atmosphere [1-6]; vertical profiles of CO_2, CO, H_2O, HCl, HF, SO_2 and aerosols are regularly inferred. CO_2 is detected from 70 km up to 165 km, CO from 70 km to 140 km, and the minor species typically below 110 km down to 70 km. Number density profiles of these species are computed from the measured spectra. N_2 and O are also considered in the model, but are not measured by SOIR. For N_2, we assume 3.5% of the total density, while O is taken as in [7].The mean profiles are presented in Figure 1.

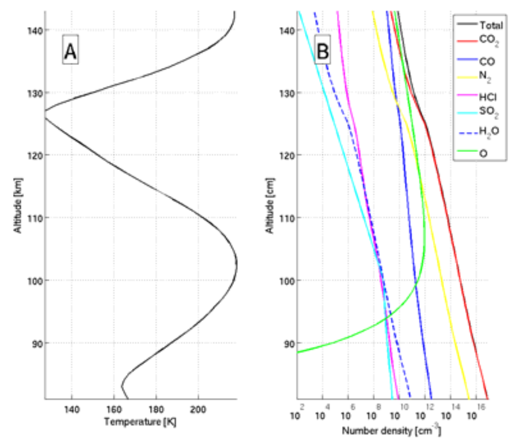

Figure 1: Panel A, mean SOIR temperature profile; Panel B: mean number SOIR number density profiles

Temperature profiles are obtained while computing the spectral inversion of the CO_2 spectra combined with the hydrostatic law [8], see Figure 1. The time variability of the CO_2 density profiles spans over two orders of magnitude, and a clear trend is seen with latitude. The temperature variations are also important, of the order of 35 K for a given pressure level, but the latitude variation are small.

2. The radiative model

A 1D radiative transfer model has been developed to reproduce the SOIR terminator profiles, derived from the Mars thermosphere code presented in [9]. This model has been expanded to better account for the CO_2, CO, and O non-LTE radiative heating and cooling processes which have to be considered in the dense atmosphere of Venus. Radiative cooling by minor species detected by SOIR (e.g. HCl, SO_2, and H_2O) are found to be small in comparison to the

15 µm CO_2 cooling. Aerosol cooling in the 60-90 km altitude range may be important to reach the thermal balance. The radiative terms are plotted in Figure 2.

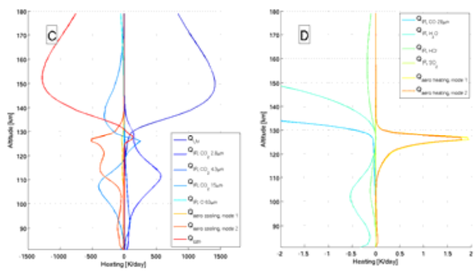

Figure 2: Radiative terms at steady state for which the model temperature best matches the SOIR mean profile. The profiles are separated in two panels as a function of their magnitude.

There is a good agreement between the 1D model temperature profile and the mean SOIR temperature profile. Further we can suggest parameters that can be adjusted to improve the agreement between model and measurements. The remaining differences can be attributed to the atmosphere dynamics at the terminator.

3. Summary and Conclusions

We developed a 1D radiative transfer model to study the thermal profiles at the Venus terminator. We considered the main species present in the Venus mesosphere and thermosphere, together with the aerosols. Aerosols need to be added to cool the mesosphere and to correctly fit the SOIR mean temperature profile.

Acknowledgements

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Rapid lithification masks the Venus sedimentary cycle

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Abstract

Venera lander data are usually assumed to indicate basaltic lavas but a significant fraction of the rock material must be volatiles, such as sulphur, implying at least strongly weathered basalts. The lander images most closely resemble sedimentary material, with layered strata (which may be pyroclastic in origin) that are sometimes broken into cobbles and fine grained sediment. The Magellan SAR was relatively insensitive to loose fine-grained material under Venus surface conditions but the reprocessed data reveal a range of weathering processes, particularly at higher elevations, and mass wasting of steep slopes. Mean wind speeds are strongly altitude dependent and are able to erode and transport material throughout the highland regions. In some areas, this material is deposited on adjacent plains where, under the extreme Venus surface conditions, lithification is an apparently rapid process. Thus the largely featureless plains may not be igneous at all but sedimentary in origin. The settling out and lithification of sedimentary material is consistent with observed crater degradation, in which low-lying crater floors are infilled first.

1. A Sedimentary Landscape

These detailed observations of surface processes challenge accepted views about Venus and reveal a much more complex and active geological picture, with evidence for a complete sedimentary cycle and significant exchange of materials, particularly volatiles, between the interior and atmosphere.

Ten spacecraft, all Soviet, have successfully operated on the Venus surface, including the first ever successful landing on another planet. With the possible exception of Venera 8, the X-ray fluorescence and γ-ray spectrometry data obtained by a number of these landers were all interpreted to indicate weathered basalts (Barsukov et al., 1982), consistent with the extensive volcanism evident in Magellan imagery. However, the four landers to successfully return surface images, Veneras 9, 10, 13 and 14, show little in common with basaltic flows on other planets.

The simplest interpretation is that while the surface materials are geochemically basaltic in origin, the primary igneous rocks were weathered, transported and deposited as wind-blown sands that lithified into sandstones. From their appearance, chemistry and mechanical properties the rocks might best be described as lithic arenites. Some time after lithification, these rock were jointed, perhaps by tectonic processes, weathered and then disaggregated into well graded gravels, with any fines removed by wind, presumably to be deposited elsewhere in a repeat of the cycle.

2. Mass Wasting

Further evidence for a sedimentary cycle is apparent in Magellan imagery (Figure 1). Venera 9 is inferred to have landed on a talus slope. Small-scale steep slopes are very common on Venus, most often associated with normal faulting and graben, and mass wasting is an equally common and probably frequent occurrence (Malin, 1992). At higher elevations, these materials appear to be strongly affected by surface winds but counterintuitively the mass wasted slopes have reflectivity characteristics consistent with lithified sediments, not loose accumulations. The low resolution of the altimeter (from which the density of surface materials is derived) of course implies a mixed signal—the red areas may well be a mixture of high dielectric (highland) material and sediments, while the green areas to the east may likewise be a mixture of talus and volcanic rock—but even relatively large areas of streamlined material have the signature of lithified sedimentary rock rather than loose regolith. Lithification must therefore be relatively rapid, as might be expected under the supercritical PT conditions of the Venus surface.

3. Conclusions

The Venus landscape consists mainly of sedimentary materials, with little evidence of volcanic rocks, in stark contrast to the global picture of a planet dominated by volcanism. Geochemical data imply that the sedimentary materials were of volcanic origin and subsequently weathered and transported. Rather than an absence of sediment supply, the lack of extensive regolith may be a consequence of relatively rapid lithification in the supercritical fluid atmosphere, with carbonate (calcite) and/or sulphate (anhydrite) the most likely cements.

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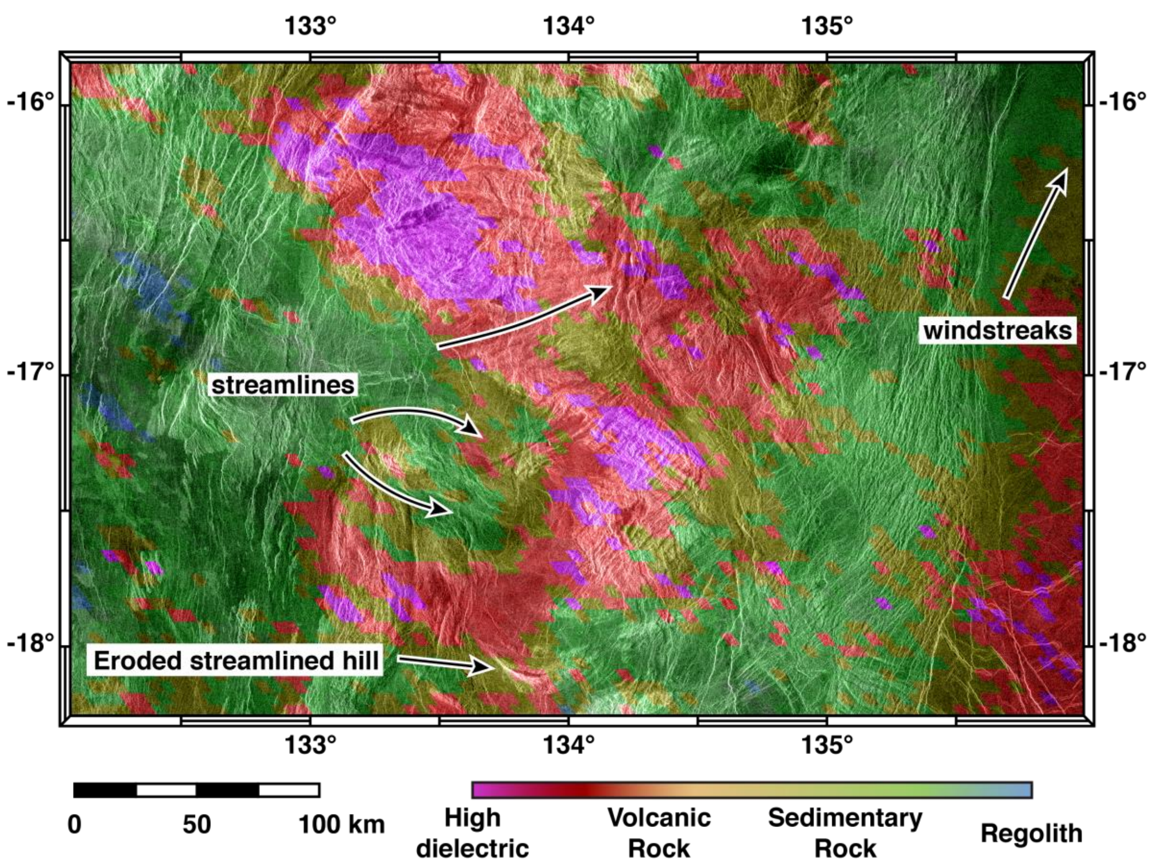

Figure 1: Windblown sediments in south east Thetis Regio shown on derived surface materials.

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Venus atmosphere and extreme surface topography

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Abstract

The temperature fields at several levels in the Venus mesosphere (60-95 km) as well as the altitude of the upper boundary of clouds retrieved from Venera - 15 (FS-V15) [1], and the zonal wind fields and albedo of the upper clouds, measured by VMC Venus Express [2], and altitude of the upper boundary of clouds VIRTIS-M VEX [3] data are compared with the topographic map, obtained by Magellan [4] . The results show that the isotherms and the altitude isolines of the upper clouds boundary reproduce the extended surface features Ishtar and Atalanta Planitia. In turn, the shapes of wind isovelocities and albedo at the upper boundary of clouds (VMC) closely follow the details of relief of Terra Aphrodite as well the isolines of altitude of the cloud tops (VIRTIS). In all cases the isolines are shifted with respect to topography by about 30° in the direction of superrotation. Non-hydrostatic general circulation model of the Venus atmosphere [5] demonstrates that the major topographic features such as Maxwell Montes and Terra Aphrodite provide a prominent impact on the atmospheric dynamics at levels as high as 90-95 km.

1. Data sets and results

We study the traces of influence of the Venus' major topographic features like Ishtar and Aphrodite on the Venus atmosphere.

1. From FS-V15 data the 3-D temperature and clouds fields in mesosphere were retrieved [1]. Earlier it was found that distribution of temperature is described by the Fourier decomposition with 1, 1/2, 1/3, and 1/4 days and upper boundary of clouds (1, 1/2 days) harmonics in Solar-fixed coordinates. The amplitudes of the thermal tide harmonics with wavenumbers 1 and 2 reach 10 K. We found that in the Sun- fixed frame of reference, both maxima and minima are shifted from noon and from midnight to westwards. The temperature field at 65 km in latitude-longitude coordinates shows a good correspondence between topography (Ishtar and Atalanta Planitia) and temperature perturbations (coefficient of correlation CC>0.9). In Fig 1 we show the isotherms of temperature overlaid the Magellan topography map. We found a good correspondence also between altitude of clouds tops and relief (Fig.2). Based on FS-V15 data we cannot compare separately the solar and topographic longitudes, as we didn't observe Ishtar at different local time. Temperature and clouds maps in comparison of the map of Magellan topography show that the perturbations are shifted by ~30° in the direction of superrotation (Fig.1, Fig. 2).

2. The other set of data we consider is the wind speed estimates near the cloud tops, obtained from the UV VMC images [2]. It was found that zonal wind speed correlates with relief (CC > 0.9) in such a way that the extended spot of low wind speed in the region of Terra Aphrodite. A local decrease of the wind speed exceeds 20 m/s. (Fig.1.). The 'image' of the relief on the clouds tops is shifted by 30° to westward direction. Although the observations we used cover the dayside only, the measurements were averaged for many orbits, with local time varying over the day.

3. The altitude of upper boundary of clouds was retrieved from the depth of the CO_2 absorption band at 1.5 μm (VIRTIS-M) [3]. The cloud tops altitude isolines are given in Fig 2 with shift of 30 ° to topography. They also show a good correlation. In Fig. 2 we show the albedo map (VMC), also shifted.

2. GCM simulations

Non-hydrostatic general circulation model of the Venus atmosphere demonstrates that major topographic features such as Maxwell Montes and Terra Aphrodite provide prominent impact on the atmospheric dynamics as high as at 90-95 km[4]. This impact is revealed in the areas of enhanced downwelling airmass flow, shifted by 30-70 degrees in longitude relative to Venus' topography. This is consistent with the hypothesis of westward propagating gravity waves, whose amplitude increases in altitude, as the ambient air density drops. The wavelength and phase velocity is constrained by the waveguide dispersion properties, which in turn are determined by the vertical profile of static stability and zonal flow.

3. Conclusions

We study the different kinds of data, obtained at different time by different methods in the different experiments, with time gap of 30 years (Venera-15 and VEX).We found that Major topographic features as Ishtar and Terra Aphrodite perturb the atmosphere. At altitudes of the upper boundary of clouds the surface "image" is observed in the zonal wind, temperature, altitude of the cloud tops in TIR and NIR and albedo in UV shifted by 30° (this value, initially found for the wind, fits good the other maps). The upper boundary of the clouds may be of several kilometers higher above the mountings, the UV albedo is about 20 % higher above Aphrodite, but wind speed is of 20 m/s lower. (It is worth noting that the variation of thermal zonal wind found from FS-V15 caused by the thermal tides even exceeds this value).

Modeling with non-hydrostatic general circulation model of the Venus atmosphere supports the expected impacts of highlands of Venus surface on dynamic of Venus atmosphere at least up to 100 km altitude. A strong correlation with the relief features, and similar shifts enables to conclude that in all cases we deal with stationary waves, connected to thermal tides linked with the surface topography, non-migrating thermal tides, so common for Mars. The work is in progress now.

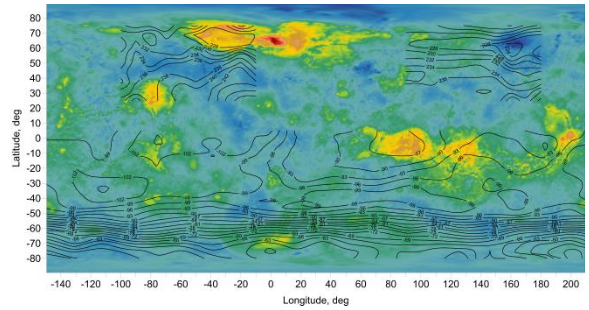

Fig.1. Isotherms at upper boundary of clouds (Venera-15) in the Northern hemisphere and isolines of the zonal wind speed in the Southern hemisphere (VMC) plotted on the Magellan topography map

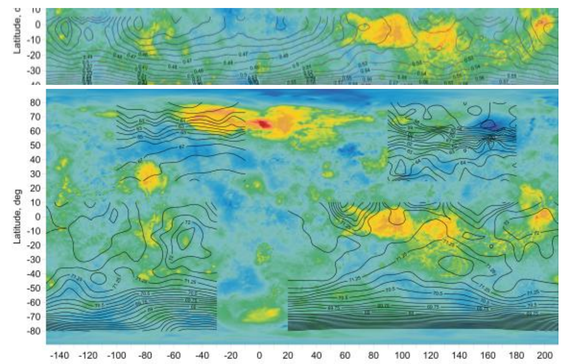

Fig 2. Upper: S-latitudes:Venus albedo in UV (VMC VEX). Low: N-latitudes - isolines of altitude of the upper boundary clouds, τ at 1218 cm-1; S-latitudes - altitude of upper boundary of clouds influence the atmosphere NIR spectral range overlaid the Magellan topography map.

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Context images for Venus Express radio occultations: a search for a dynamical-convective origin of cloud-top UV contrasts

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Abstract

In this paper, we present a comparative analysis between data from the Venus Express Radio Science experiment (VeRa) and the Venus Monitoring Camera (VMC) UV channel. We compare the temperature structure derived from VeRa measurements with VMC-UV brightness at that same location, in search for any correlation. In the data analysed to date – which were all obtained at high Southern latitudes – we find no strong correlations, implying that we can find no evidence for a dynamical-convective origin of the UV contrasts at these latitudes. We suggest that the contrasts are formed at lower latitudes, a hypothesis which will be examined by looking at lower-latitude observations.

1. Introduction

It has been known for many decades that Venus shows strong contrasts when observed at UV wavelengths, as opposed to longer wavelengths in the visible and NIR, where Venus looks very homogeneous. This has been explained by the presence of a so-called UV absorber, which chemical identity is still unclear. Two hypothesis concerning the source and distribution of the UV-absorber have been put forward. For one of them the argument is that the absorbing substance is being transported from below the clouds up to the cloud top level by means of convection. This implies that in regions with more convection the absorber would be more abundant at the cloud-tops, thus resulting in lower brightness when observed in the UV. In the other scenario, it is haze-forming material which is brought to the cloud-tops by convection; in this case regions with stronger convection produce higher cloud tops would therefore show brighter in the UV.

The premise behind the current analysis is to combine data from the Venus Express Radio Science experiment (VeRa) and from the Venus Monitoring Camera (VMC), to search for any correlation between the temperature structure (T_z, $[dT/dz]_z$, static stability, S_z) as sounded on one specific location and the UV brightness of that same location.

2. Data

Between 25 November and 31 December 2013 a special observing "South Polar Dynamics" campaign was performed with Venus Express (Figure 1). On

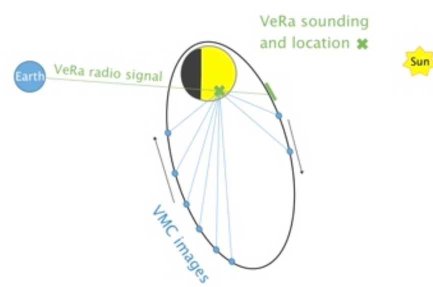

Figure 1: Geometry for the late 2013 South Polar campaign

each orbit one VeRa atmosphere sounding was acquired shortly after the pericentre passage, as well as a series of VMC-UV images capturing the very VeRa sounding location on that orbit before and after the sounding as it moves across the planet pushed by the zonal and meridional winds. The sounded latitudes varied between -83º and -48º. An example is shown in Figure 2.

We used the average wind field data from [1] to correct for wind motion in the interval between the VeRa sounding and each VMC image. An example of a selection of images from one orbit is shown in Figure 3. We did attempt to use wind tracking data specifically obtained from images on each orbit, but we found the dispersion in these data was too large to provide meaningful results.

Once the wind-corrected VeRa-sounded location was

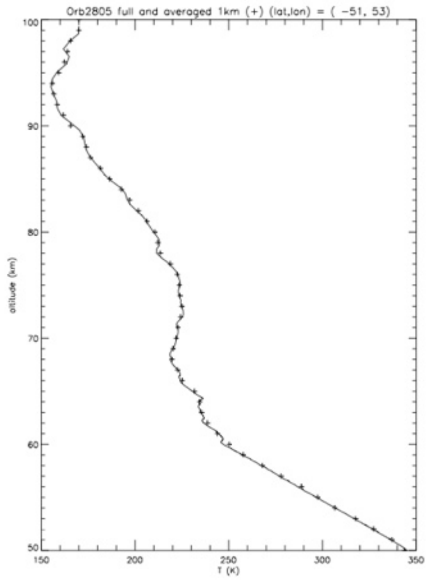

Figure 2: Example of a resulting T(z) from VeRa sounding (25 Dec. 2015).

identified in each VMC-UV image, the relative UV-brightness was determined from the whole series of images at the locations of the VeRa sounding for each orbit, taking into account the changing viewing geometry (phase angle, incidence angle and emergence angle).

3. Analysis

The question is whether or not we can identify any statistically significant correlations between the temperature structure at a given location and the relative UV-brightness (Br) at that same location. We compare T_z and $[dT/dz]_z$ and S_z for levels between 50 and 80km altitude to the relative UV brightness for 30 orbits. No significant correlations have been found at the time of submission of this abstract. At the moment, we are extending our analysis to a wider dataset, including an another ~ 60 orbits with VeRa sounded latitudes closer to the equator.

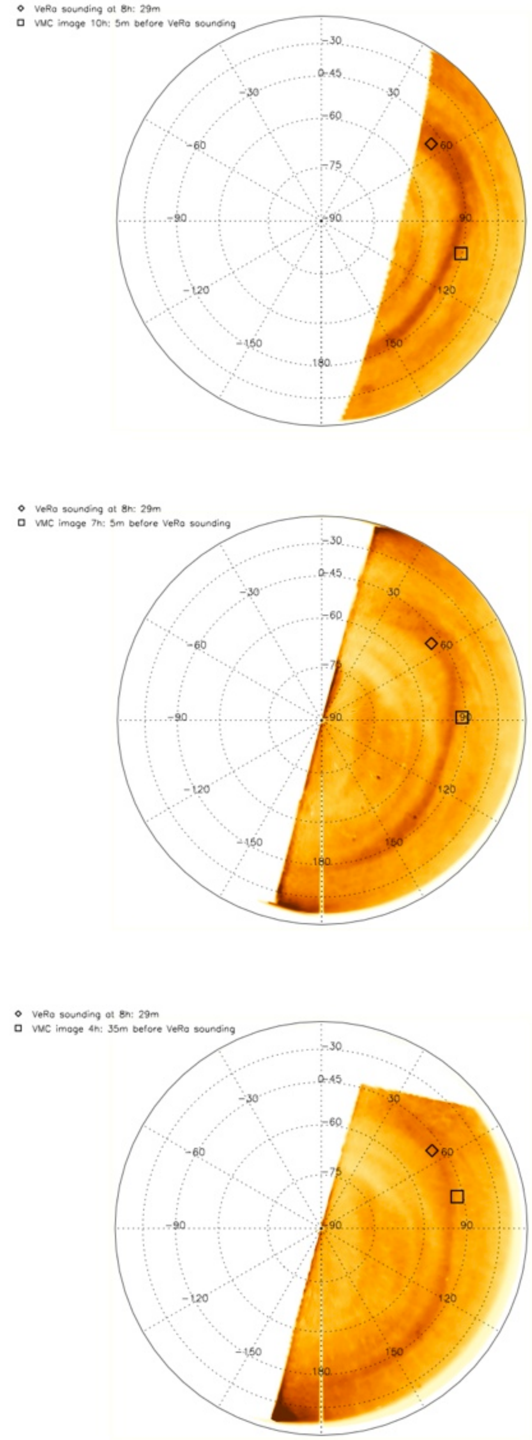

Figure 3: VMC UV 25 Dec. 2015. Diamond is the Vera sounded location, square is that same location at the time of the image at 10h, 7h and 4.5h before the VeRa sounding.

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Visibility of Active Lava Flows from Venus Orbit

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Abstract

I present a model of the signatures of active lava flows observable through spectral windows from orbit and data processing methods for isolating these signatures in near-infrared images. The model estimates the thermal emission of lava flows based on models for the analysis of remote observation of eruptions on Earth and Io, however adjusted to the different thermal environment of the Venus surface. This thermal emission radiation is only partially transmitted through the diffusely scattering cloud layer and moreover diluted over a diameter of 100 km, an area much larger than the size of most flows. Data processing methods to enhance the chance to detect these signatures include corrections for variable cloud opacity using other spectral bands, subtraction of background thermal emission, and spatial filtering. This model and the implementation of the data processing methods for VIRTIS IR data, arguably the most sensitive and extensive applicable dataset, indicate that only very large and intense eruptions could have been detected with existing data.

1. Introduction

The surface of Venus is geologically young compared to other terrestrial planetary bodies except Earth and Io. Most of the young surface has an origin in effusive volcanism, however a wide range of global rates of volcanism is discussed for Venus. This is due to the fact that the cratering record of the surface - shielded from impacts by the atmosphere - does not constrain whether the volcanism occurs constantly or episodically through time. A significant constraint on the current volcanic activity would contribute much to this discussion. The Venus Express mission included the imaging instruments VMC and VIRTIS, which had the capability to observe volcanic activity. No clear signatures of active volcanism have been reported for VIRTIS M IR data, however transient bright spots in VMC images have been interpreted as most likely to be caused by eruptions [7].

2. Signatures of active lava flows

Thermal emission of active flows: Lava flow thermal emission is modelled as a function of time assuming an effusion rate and flow thickness, which constrains areal growth and age of the flow surface. The flow surface cools rapidly, which greatly diminishes the contribution to thermal emission (Fig 1). The surface cooling occurs mostly by radiation and convection. On Venus surface winds are low and free convection and radiative cooling are coupled due to the IR opaque CO_2 atmosphere [8], which reduces efficiency of both. I assume that an area fraction of 0.1 to 10 % of the flow area corresponds to fractures and exposes lava for only a few seconds, consistent with Earth observations [1]. Finally the model imposes a limit on the areal growth and thus thermal emission if the total heat loss of the flows of the eruption reaches a certain fraction of the heat supplied at the vent, as it is assumed in studies of Earth and Io remote sensing data of eruptions [eg. 3,2].

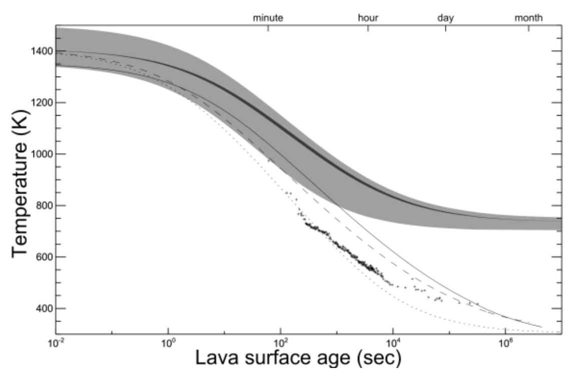

Figure 1 Lava surface temperature as function of time since eruption for Earth and Venus under various assumptions.

Atmospheric scattering: Active flows which are not immediately obvious due to their brightness, are small compared to the area over which its emission is scattered by the atmosphere. Thus I model them as a point source adding to the background radiance. The radiance distribution of a point source observed at the top of the atmosphere is approximately a Gaussian with a full width half maximum of 100 km [4].

3. Data processing methods

Cloud correction: The cloud opacity is variable, and the signature of an eruption needs to be distinguished from this variability in order to be unambiguously detectable. In order to reduce this variability it is possible to correct for cloud opacity if simultaneous observations at a wavelength where the emission originates below the clouds but above the surface are available [5], e.g. the 1.31 micron band of VIRTIS.

Background subtraction: The background thermal emission can be estimated based on altimetry as proxy of surface temperature [6], however if longterm observations of the surface in question are available it is additionally possible to account for variable surface emissivity. By subtracting the average radiance over time, short term deviations such as eruptions, are more visible.

Spatial filtering: Since the size of an eruption signature is well known, it is possible to spatially filter the data. The most straightforward is a filter with highpass properties, such as subtraction of a moving average with a diameter larger than 100 km. This removes residual cloud variation and instrumental straylight. If the instrumental resolution is high enough, a highpass filter additionally can reduce instrumental noise.

4. Conclusions

Using the above data processing on VIRTIS-M IR data I estimate that it would be very likely to detect active eruptions with 1 km^3 lava effused within 10 days or a sustained effusion rate of >800 m^3/sec. This corresponds to a 1GWum^{-1}sr^{-1} signature, with a maximum that is ~1.2 times background emission. Under less conservative assumptions the same brightness can be achieved with 0.01 km^3 lava and effusion rates >30 m^3/sec. [9] presents historical eruption data from 1840 to 1980 for three volcanos that can be compared to these detection criterions (Fig. 2). Only under optimistic assumptions some of the more intense eruptions would have been detected, had they happened in the field of view of VIRTIS. The bright spots observed by VMC at Ganiki Chasma, with an emerging flux of more than 2 times the background [7], would be consistent a lava flow of at least 250 m^3/sec even with optimistic assumptions. On Earth this is a rare event on historical timescales. Several eruptions like this per year on Venus could significantly contribute to ongoing resurfacing on geological timescales.

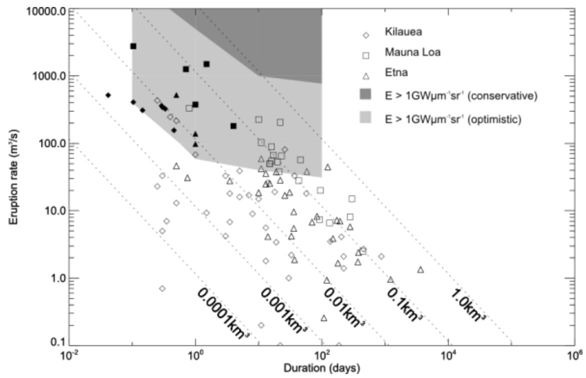

Figure 2 Historical eruption data compared to the capability of VIRTIS to detect eruptions for different assumptions.

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