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Surface brightness variations seen by VIRTIS on Venus Express and implications for the evolution of the Lada Terra region, Venus

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[1] Venus Express is since April 11, 2006 in orbit around Venus. VIRTIS (Visible and Infrared Thermal Imaging Spectrometer) has started only hours after orbit insertion to collect an immense and unique data set. Of special interest is the wavelength range from 1–1.5 microns which includes the "atmospheric windows". By averaging several hundred multi-spectral images obtained during the mission we have been able to map the surface temperatures for almost the whole southern hemisphere of Venus. Blurring in the clouds limits the spatial resolution to approximately 100 km globally. The most exciting and at the same time the most complex task is to retrieve compositional information for the surface of Venus from the hyperspectral data obtained by VIRTIS. We report here about indication for variations in the surface composition in the Lada Terra region based on brightness variations mapped from VIRTIS measurements and present some tentative links to the evolution of this region.
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1. Introduction

[2] The M-IR channel of VIRTIS [*Drossart et al.*, 2007] allows observing the surface of Venus in three small atmospheric windows at 1.02, 1.10 and 1.18μm. While the atmospheric windows show little CO_2 absorption on its way through the atmosphere, the thermal radiation is modified by scattering by clouds. Variations in the optical thickness of the clouds modulate the spatial distribution of upwelling radiation. Multiple reflections between surface and clouds generally wash out image contrast from surface emissivity. We have developed a data processing pipeline based on the approach by *Hashimoto and Sugita* [2003] which allows processing the huge amount of data returned by VIRTIS in a timely manner.

[3] The results of this approach are ambiguous since neither surface emissivity nor surface temperatures are well known. This means that only one of these quantities can be retrieved at a time based on reasonable assumptions for the other quantity. Surface temperature is assumed to be mostly a function of altitude and no diurnal or seasonal variations are expected. Therefore the whole VIRTIS data set can be used to derive an altitude temperature relation. Focusing on individual regions, brightness anomalies can be retrieved as differences between the global average and locally observed temperatures. Assuming that the atmospheric correction does not introduce artifacts, these should be first order anomalies and related to the surface properties. This allows us to map for the first time tentatively the distribution of different surface types on Venus based on the near IR spectral data. The 1.02 μm window exclusively used in this study is mainly sensitive to the FeO content of the material and allows thus to map the distribution of mafic materials.

2. Data Set and Data Processing

2.1. Limitations on the VIRTIS Surface Data Set

[4] For this study we have used data from the IR channel of VIRTIS-M. This channel covers the wavelength range from 1–5μm with a spectral resolution of typically 12 nm. Given the orbital velocity of Venus Express and the highly elliptic orbit VIRTIS-M can obtain multispectral images only for altitudes larger than approx. 10000 km. Below this altitude there will be gaps between the individual stripes. This restriction limits the coverage for surface mapping by VIRTIS to the southern hemisphere. On the northern hemisphere only spot observations are possible.

[5] The best obtainable spatial resolution from an altitude of 10000 km would be approx. 16 km given the optical parameters of VIRTIS-M. However, any photon that is emitted from the surface will encounter multiple scattering at particles in the clouds in a way that results in a blurring of the images. Models have predicted a limit of the spatial resolution of 50–100 km [*Hashimoto and Sugita*, 2003; *Moroz*, 2002]. For the observations discussed here the spatial resolution is over 100 km/pixel.

2.2. Data Processing

[6] The data pipeline developed for VIRTIS takes raw data and corrects brightness for various atmospheric influences applying a semi-empirical approach [*Müller*, 2007]. The resulting images are map-projected, averaged and mosaicked.

[7] First atmospheric effect to be removed is sunlight scattered in the uppermost cloud and haze layers. Spatial distribution of this sunlight is retrieved from bands close to 1.4μm where Venus does not emit [*Meadows and Crisp*, 1996]. A proportional amount of radiance is subtracted at the wavelengths of interest. The necessary coefficients are obtained from linear fits to window radiances as functions

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of radiance at 1.4 μm. Similarly limb darkening is corrected for by division of an empirically derived linear function of cosine of emission angle into the images.

[8] To remove contrast due to scattering in the clouds a simplified atmospheric model is used, following the approach developed by *Hashimoto and Sugita* [2003]. The currently used model does not allow a reliable direct retrieval of the absolute emissivity of the surface because the result is strongly affected by non-linearly enhanced noise. Therefore for this study we focus on brightness variations which are related to emissivity variations. The approach is based on a two stream approximation of radiative transfer in a conservatively scattering, plan-parallel grey atmosphere that describes the influence of multiple reflections between atmosphere and surface on the emerging flux.

[9] When studying the relation of flux at 1.02 and 1.31 micron in the VIRTIS data and assuming an average cloud reflectivity of 0.82 [*Hashimoto and Imamura*, 2001] we find that the integrated albedo of atmosphere and surface below 25 km is on average 0.8 at 1.02 micron.

[10] With the assumption of a constant lower atmosphere albedo of 0.8 and variable cloud transmittance derived from 1.31 micron, the emerging flux at 1.02 micron corresponds to a integrated lower atmosphere and surface brightness temperature highly correlated with the Magellan altimetry data and a temperature lapse rate of −5 K/km.

[11] Expected emissivity and surface temperature lapse rate of the basaltic surface is 0.85 or more and −8 K/km respectively. Gas-related absorption/emission, Rayleigh scattering and aerosols in the lowest atmosphere clearly have an impact on the thermal emission of the surface as seen from the values obtained for the 25 km height [*Moroz*, 2002; N. Müller et al., Venus surface thermal emission, submitted to *Journal of Geophysical Research*, 2008].

[12] There is, however, no evidence yet of any horizontal spatial variability of composition or temperature in this layer [*Meadows and Crisp*, 1996] therefore it is sound to assume that the retrieved brightness temperature is composed of two different components, one correlated with the surface topography including thickness of the atmospheric layer and the surface temperature, and one related to surface emissivity that is not correlated with topography. The correlation of the image brightness with topography is removed by division of Magellan altimetry [*Tyler et al.*, 1992] projected on image viewing geometry and scaled with the global relation of brightness and Magellan altimetry.

[13] This residual signal that is not correlated to viewing geometry, straylight, cloud opacity and topography is very weak compared to noise but it is time-invariant. Therefore the deviation of the ratio from unity is dubbed brightness anomaly, considered to indicate variation in surface emissivity, and projected on a common grid of coordinates and stacked using a median over time to obtain a single map.

3. Brightness Variations in Lada Terra

[14] We discuss here, as an example, parts of the Lada Terra region and focus on the Quetzalpetlatl Corona. A global discussion of emissivity variations seen by VIRTIS will be the topic of a follow-up publication by Müller et al. (submitted manuscript, 2008). The approach used to retrieve surface brightness variations seems very stable in this region and we see spatial variations in surface emissivity that showing correlations with geological features known from Magellan radar images [*Ford and Pettengill*, 1992].

[15] Composite images from Magellan, and Arecibo data, have been used previously to analyze the corona itself as well as the nearby lava flow field [*Solomon et al.*, 1991; *Senske et al.*, 1991; *Baer et al.*, 1994; *Ivanov and Head*, 2003, 2006]. Most recently *Kratter et al.* [2007] used new Arecibo observations to study the properties of the flows associated with Quetzalpetlatl Corona in details.

3.1. Lada Terra Region As Seen by VIRTIS-M

[16] The surface coverage by VIRTIS on Venus Express is not homogenous. After 1.5 years of surface observations by VIRTIS Lada Terra is among the best covered areas so far, making it an ideal target for this study. The 297 images that at least partly cover the area have been obtained in two consecutive Venus nights. Only images with exposure times longer than 3.3 seconds and obtained at a spectrometer temperature between 152 K and 156 K are included. The latter selection is necessary to reduce effects induced by wavelength shifts as the spectral calibration of VIRTIS is temperature dependent (for details, see Müller et al. (submitted manuscript, 2008)). In general, in this study only data with a high signal-to-noise ratio are included.

[17] The resulting brightness anomalies are shown in Figure 1. Areas with a significant positive or negative brightness anomaly have been visually traced and outlined by the solid line. Three areas with pronounced positive anomalies are indicated by a black outline (labeled 1–3 in Figure 1), one area with a negative anomalies by a red outline (labeled 4 in Figure 1). Taking into account the limited spatial resolution and the noise remaining in the data only areas of larger extend have been outlined. The areas show no clearly defined boundary. Therefore, for all areas an inner area and an outer area reflecting a gradual transition to the background values (indicated by the dashed line) have been mapped.

[18] In addition to the outlined areas some linear emissivity anomalies are seen, mainly in the lower right corner of Figure 1, marked by a semitransparent grey box. This region has the lowest coverage with only a few images overlaid. Any remaining artifacts in the single VIRTIS images (for example due to straylight) are not fully removed by the averaging procedure. For the purpose of this study anomalies in this area are therefore not considered.

[19] With the stringent data selection the best effort has been made to ensure that the observed brightness anomaly is real and not an artefact of the data processing and that it is indeed surface related.

3.2. Correlation Between Morphology and Brightness Anomalies

[20] Figure 2 shows a mosaic of left- and right-looking SAR images of the area obtained by the Magellan spacecraft [*Ford et al.*, 1993]. Areas where Magellan topography is unavailable have been masked because the VIRTIS data processing relies on an a priori knowledge of the altimetry.

[21] The anomalies as outlined on the VIRTIS data have been transferred to the SAR image to assess any possible correlation with surface units. While none of the areas

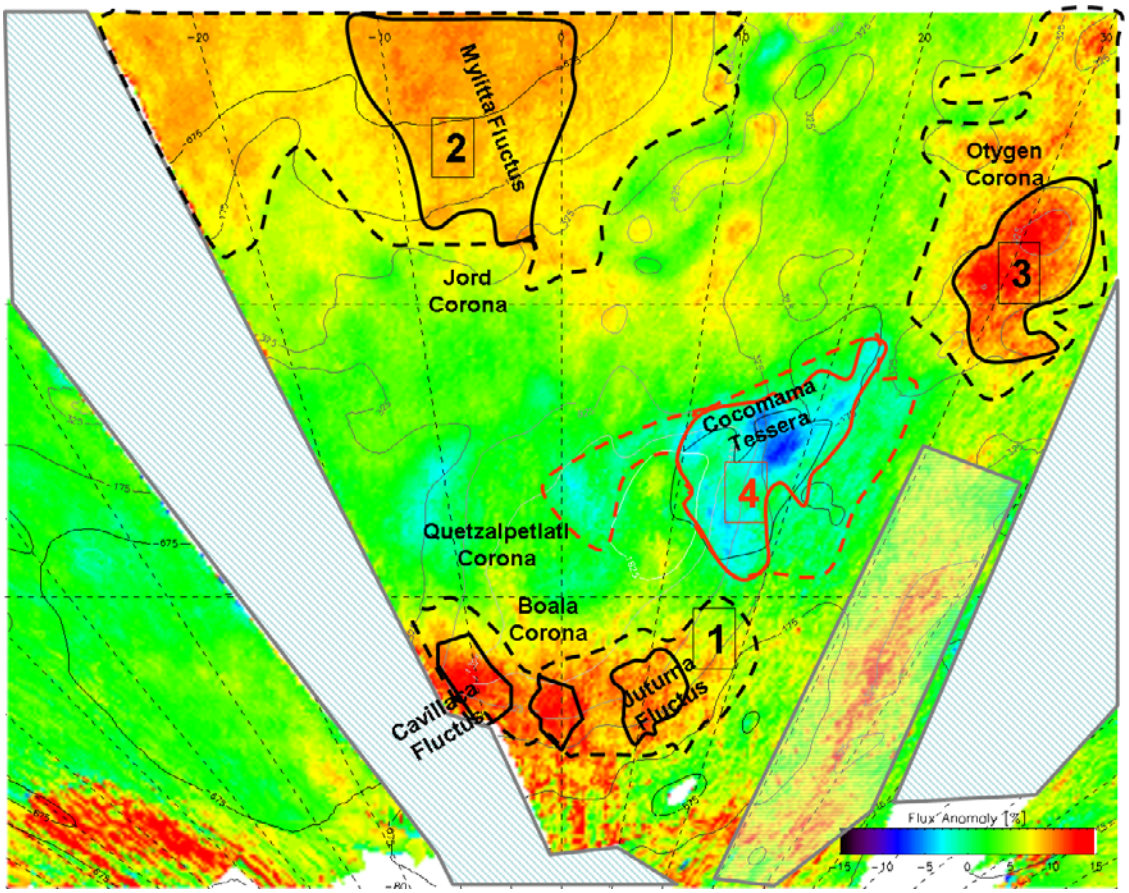

Figure 1. Variations of the surface brightness for the Lada Terra region in the 1.02μm atmospheric window as observed by VIRTIS on VenusExpress in sinusoidal projection. Outlined are the 4 areas of anomalies identified in this study–areas with missing Magellan altimetry data or low VIRTIS data coverage have been masked out.

shows perfect correlations to radar-sounded surface unit, their spatial extend and distribution is indicative for the possibility that certain correlations between the VIRTIS data and the surface units may exist. Most evident are the correlations for areas 1 and 2, both coinciding with lava flows. The area 1 covers most of the young lava flows at the south and southwestern flank of Quetzalpetlatl Corona, whereas the area 2 coincides with the Mylitta Fluctus lava flow at the north flank of Jord Corona. The outer extend of the area 1 is constraint within the lava flows visible on the SAR image. For the area 2, the outer limit seems to extend beyond the margins of Mylitta Fluctus. The inner anomaly area shows a good correlation with Mylitta Fluctus.

[22] For the area 3 the correlation with surface units is not so obvious. It partly coincides with lava flows associated with Otygen Corona but the outer limit of the anomaly extends much further. The VIRTIS coverage for this area is less dense than for the rest of the study area, which increases the noise level significantly. The possibility that the extent of this anomaly is partly an artifact of the data processing can not be excluded.

[23] The main negative anomaly in the area 4 shows a good agreement with the southern half of the extensively tectonized Coconama Tesserae area visible in the SAR image. The outer margins of the anomaly include several seemingly heterogeneous surface units including some of the rise of Quetzalpetlatl Corona. A comparison with the SAR mosaic shows that the area 4 in general seems to have a distinct morphology characterized by a significant fracturing of the surface. It has to be noted however that not the entire fractured unit shows an anomaly in the VIRTIS data.

3.3. Interpretation of the Observed Emissivity Variations

[24] The combined VIRTIS-Magellan data set in its present state does not allow an unambiguous interpretation of the observed emissivity variations. The spatial correlation of the positive anomaly with relatively young lava flows and of the negative anomaly with fractured and therefore most likely older regions implies a component that is age dependent. For now we propose two tentative interpretations – an endogenic and an exogenic interpretation. The endogenic interpretation considers that the brightness anomalies observed by VIRTIS are related to material of different composition deposited on the surface.

[25] The areas 1 and 2 are related to lava flows. In both cases the lava flows superimpose the surrounding material and they can thus be assumed to be relatively young [*Roberts et al.*, 1992; *Magee and Head*, 1995; *Ivanov and Head*, 2006]. Quetzalpetlatl Corona is the third largest corona on Venus [*Ivanov and Head*, 2003, 1996; *Stofan et al.*, 1992], and its flows are the largest in length and area on the planet. The source regions for these flows appear to be in and around Boala Corona. One of the most obvious

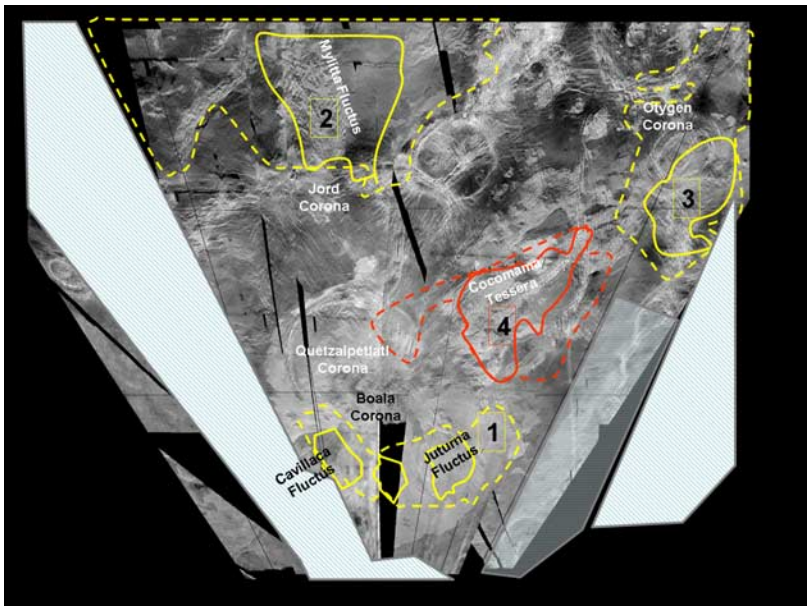

Figure 2. Mosaic of Magellan SAR images covering the same region as the brightness variation map in Figure 1. The areas mapped from the VIRTIS data have been overlaid on the Magellan SAR images. Colors of the outlines have been adjusted to increase readability.

source regions is an arcuate graben just to the south of Boala Corona. There are also several shield volcanoes within Boala Corona, which *Ivanov and Head* [2003] cite as sources for some of the flows. It is thought that several separate episodes of eruption occurred because superposition of different flow complexes is evident in some regions [*Ivanov and Head*, 2006]. Mylitta Fluctus is a generally radar-bright lava flow superimposed on darker plain material. It seems to emanate from a single source region in the linear deformation zone of Kalaipahoa Linea [*Roberts et al.*, 1992]. The individual flows in this lava complex have a length of up to 800 km and a width of 3 to 125 km. This puts the individual flows at the lower limit of the spatial resolution achievable by VIRTIS.

[26] The formation of the Quetzalpetlatl Corona and the volcanic activity of Mylitta Fluctus [*Roberts et al.*, 1992] have been linked to the formation of the rift zone in Lada Terra in response to downwelling in Lavinia Planitia. Specifically for Quetzalpetlatl Corona *Magee and Head* [1995] proposed the uplifting of deep mantle material as possible source for the lava. The extrusion of an amount of more mafic material on the surface might be consistent with the positive anomaly seen in the VIRTIS data. *Roberts et al.* [1992] linked the activity of Mylitta Fluctus with the formation of the rift zone.

[27] This scenario may also be consistent with the positive anomaly seen in the area 3 as the Otygen Coronae also seems to be linked to the Lada Terra rift system [*Baer et al.*, 1994]. However, here the link is more tentative as the correlation with lava flows identifiable in the SAR images is much less clear than for the areas 1 and 2. We have to consider here that we see partly artifacts of the data processing comparably to what we see in the lower right part of Figure 1.

[28] The area 4 with the negative anomaly is correlated with fractured surface regions that are largely without later lava flow coverage, but are heavily embayed. The strong fracturing of these regions might indicate that they are relatively old and represent an older surface that is in most other areas covered by lava flows. This is especially supported by the correlation of the main negative anomaly with Cocomama Tessera. Therefore one might speculate that this older surface is less mafic than the later emplaced lava flows. This interpretation is, however, speculative based due to the limited amount of the available data. Fractured surface regions are especially prone for errors in the altitude determination by Magellan [*Rappaport et al.*, 1999], which would affect the retrieval procedure for VIRTIS.

[29] Assuming that the interpretation of brightness anomalies is indeed linked to differences in the surface composition we could postulate a timeline for the development of the studied area in agreement with ideas for the formation of the whole region. The oldest terrain would be the area 4 which possibly represents a more primordial surface that was tectonically deformed before the rifting of Lada Terra. The areas without any significant anomaly would represent normal mid-age Venusian surface materials, while the areas 1–3 would be relatively younger extrusive lavas [*Basilevsky et al.*, 2007]. Based on the VIRTIS observations the relatively young material would be more mafic and it may indicate the latest stages of evolution of the Lada Terra region.

[30] A competing exogenic hypothesis would incorporate a smaller degree of chemical or mechanical weathering of the younger surface units compared to the surrounding older materials. Chemical weathering implies that the atmosphere of Venus reacts with and alters the surface material. Our observation may show the difference between highly altered and less altered material. As the timescale for chemical alteration in the aggressive Venus atmosphere is basically unknown it is not possible to give an absolute timing for the emplacement of the lava flows. Mechanical weathering

implies a change of the surface texture over time. In this exogenic hypothesis the negative anomaly would be indicative for the highest degree of weathering. This is true if the areas that display the negative anomaly are indeed the oldest regions in the study area. It is, however, unclear why and how exactly this area would be more weathered that the average Venusian surface region.

[31] Currently both hypotheses are supported by the data. We lean to towards the endogenic hypotheses as the exogenic hypothesis has tighter constraints - especially the implication that the large area lava flows have been emplaced relatively recently. To resolve the ambiguities further observations are necessary. In addition, especially considering the exogenic hypotheses, laboratory measurements on the change of emissivity for altered basalts at high temperatures are needed. Plans are under way to upgrade the Planetary Emissivity Laboratory (PEL) at DLR in Berlin [*Helbert and Maturilli*, 2008] to allow measurements of the emissivity at 1μm of analog materials at temperatures typical for the Venusian surface.

4. Conclusions

[32] While there have been observations using the atmospheric windows by *Carlson et al.* [1991], *Crisp et al.* [1991a, 1991b], and *Baines et al.* [2000] VIRTIS on Venus Express allows for the first time to map systematically the surface radiance from orbit over a long period of time. The full potential of this unique data set only starts to emerge. We have shown here one example of differences on the Venusisan surface which are identifiable from the VIRTIS data set in a way that might be linked to variations in the surface composition. The example shows the potential of the VIRTIS surface observations in advancing our knowledge on the evolution of the Venusian surface. This data is highly complementary to the existing data sets from Magellan and the Russian lander probes. A further combination of these data sets might significantly add to our understanding of the evolution of Venus.

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