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UV contrasts and microphysical properties of the upper clouds of Venus from the UV and NIR VMC/VEx images

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ABSTRACT

The nature of UV contrasts observed on the upper cloud deck of Venus is still not known. To constrain better the properties of particles that may cause the UV contrasts, the phase dependences of brightness of the venusian clouds measured by the ultraviolet and near-infrared channels of the *Venus Express* Venus Monitoring Camera (VMC) in the UV dark and bright regions are jointly analyzed. The range of small phase angles, where the glory phenomenon is observed, is of key importance, since the properties of cloud particles can be reliably estimated from the shape and position of glory. However, from more than 2500 orbits of the mission, only in ten orbits the images were taken simultaneously in UV and near-IR channels at small phase angles. Their analysis have yielded the following results. In the UV dark and bright clouds of the equatorial region near the local noon, the derived radii of cloud particles turned out to be the same and rather large, 1.3–1.6 μm. No unambiguous connection between the UV contrasts and the brightness in the near-IR channel was found. In some cases, the regions that appear contrasting in UV show no difference in the near-IR brightness. This means that the properties of 1-μm mode particles are the same in these regions and only the contribution of small submicron particles differs, because the near-IR channel is weakly sensitive to the presence of particles smaller than ≈0.3 μm in radius. The difference in the composition of 10% of the number of submicron particles (if sulfur and sulfuric acid compositions are considered as probable for the submicron mode) is enough to produce the observed UV contrasts. In the other cases, the UV contrasts are accompanied by the differences in near-IR brightness. This suggests that the cloud particles of the 1-μm mode contribute to these contrasts as well. However, the modeling showed that exactly the variations in the composition of submicron particles in the clouds produce a key effect on the UV contrasts observed. Moreover, a portion of submicron particles with a high refractive index, when incorporated into the sulfuric acid aerosols during the condensation process, may provide the higher refractive index (relative to that of sulfuric acid) of the 1-μm mode derived from modeling. The glory phenomenon was also observed at latitudes 30–60°S, in the transition region from the mottled clouds in dark tropics to streaky cloud morphology at higher latitudes. This allowed the sizes of cloud particles near the frequently seen UV-bright bands to be estimated. It was found that the radii of particles in the upper cloud layer decrease from 1.05–1.2 to 0.8–0.9 μm with increasing latitude from ~35°S to ~62°S. Our present modeling also clearly showed that the high brightness in the UV-bright band is caused by an additional amount of non-absorbing (in UV) particles with $R_{eff} \approx 0.9$ μm at the cloud top and/or by the decrease of a portion of absorbing particles inside the clouds below this layer. No variations of the effect with the local solar time for the interval from 10 to 13 h available in the data were detected.

1. Introduction

Observations of Venus at visible wavelengths, even from close-up, show little or no details in the clouds, which appear to form a uniform blanket with optical depths of 20–40 over the whole planet. However, in the ultraviolet (UV) spectral range (from 0.2 to 0.5 μm), the venusian atmosphere shows variable contrast features. They were first detected in early 20th century (Wright, 1927; Ross, 1928), and further ground-based and spaceborne observations confirmed high variability in the appearance of Venus disc in UV. The UV contrasts reach 20–30%; they are thought

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to originate from some ultraviolet-absorbing substance that is non-uniformly distributed through the clouds (Esposito, 1980; Pollack et al., 1980). Many candidates, such as SO_2, Cl_2, $FeCl_3$, S_n, SCl_2, S_2O, have been proposed to explain the nature of UV-contrast features (e.g., Pollack et al., 1980; Zasova et al., 1981; Toon et al., 1982; Na and Esposito, 1997; Krasnopolsky, 2006). Sulfur dioxide SO_2 is a strong UV absorber and definitely present in spectroscopic measurements of Venus. However, its spectrum can explain only the absorption between 0.2 and 0.32 μm and does not precisely match that of Venus at longer wavelengths. This requires another absorber that has not been identified yet (Moroz, 1981; Moroz et al., 1985; Bertaux et al., 1996; Esposito et al., 1997).

The concentration and distribution of this absorber is very important for thermal balance and global dynamics of the venusian atmosphere and for the chemistry of its upper cloud layers (see, e.g., for reviews Titov et al., 2007; Mills et al., 2007). They are mostly composed of fine sulfuric acid aerosol particles photochemically produced from sulfur dioxide and water vapor (Esposito et al., 1997). A source of energy for photochemical reactions is provided by the incoming UV radiation, and, moreover, the maximum absorption of solar energy occurs at 0.35–0.40 μm, where the unknown component strongly absorbs (Pollack et al., 1980; Moroz, 1981).

The Venus Monitoring Camera (VMC) onboard the *Venus Express* (VEx) spacecraft, successfully operated in orbit around Venus since April 2006 until November 2014. It acquired a large amount of wide-angle images of the planet in four narrow spectral bands, one of which is centered at 0.365 μm, the characteristic wavelength of the unknown UV absorber (Markiewicz et al., 2007a). The images show remarkable variability in the brightness and morphology of the cloud deck of Venus (Markiewicz et al., 2007b; Titov et al., 2012; Khatuntsev et al., 2013). Though the VMC imaging cannot directly identify the nature of the unknown UV absorber, observations of clouds, especially combined with the other VEx measurements, may provide a clue for understanding the origin of the observed UV pattern and its relation to the physical conditions in the cloud layer. Titov et al. (2008) found that the observed global distribution of UV brightness and cloud morphology are closely related to the dynamical regimes of the lower mesosphere. Moreover, a clear correlation of the global UV markings with the patterns observed at thermal infrared (IR) wavelengths and in the near-IR transparency windows on the night side suggest that the UV structures on the cloud top have morphological and dynamical relation to those deeper in the clouds. From the full planetary disk observations in the UV channel of VMC, Molaverdikhani et al. (2012) estimated a global picture of the unknown absorber abundance and its vertical distribution. Their best models describe the unknown absorber either well-mixed with sulfuric acid above the bottom of the upper cloud layer (≈63 km) or composing a thin layer near the cloud deck top (≈71 km), yielding the average opacity of the unknown absorber increasing from 0.08 ± 0.05 to 0.21 ± 0.04 in the polar and equatorial regions, respectively.

In the present paper, to estimate the properties of the cloud particles in the UV dark and bright regions, we analyze the phase dependences of brightness of small cloud areas. These dependences are obtained from the sets of VMC images taken at phase angles $\alpha \leqslant 40°$, where the glory phenomenon can be observed at the upper deck of the Venus clouds. The glory pattern appears at scattering on spherical particles with a very narrow size distribution (e.g., Hansen and Travis, 1974; Hansen and Hovenier, 1974; Adam, 2002; Laven, 2005); and, as was confirmed in our previous studies, the angular position of the glory feature allows for very precise estimate of the size of particles in the upper clouds of Venus (Markiewicz et al., 2014; Petrova et al., 2015; Shalygina et al., 2015). Moreover, the analysis of the near-IR data (0.965 μm) showed that the details of the glory feature sometimes could not be explained by scattering by purely sulfuric acid droplets and required presence of an additional component with a higher value of the real part of the refractive index. This material can be ferric chloride $FeCl_3$ or sulfur allotropes S_n, which both are considered as candidates for the unknown ultraviolet absorber (e.g., Krasnopolsky, 2006; Mills et al., 2007). There are some evidences (see Ekonomov et al., 1984; Krasnopolsky, 1986; Esposito et al., 1983, 1997 and references therein) that the absorber is at the altitudes of the upper cloud layer (57–70 km). We suggested that this UV-absorbing component is initially in some portion of the submicron particles; under proper conditions, these submicron particles participate in the condensation of sulfuric acid droplets in the clouds and form the complex UV-absorbing particles with a refractive index higher than that of sulfuric acid. This scenario and the relationship of ferric chloride and different forms of sulfur to the sulfuric acid cloud droplets were discussed, for example, by Zasova et al. (1981), Toon et al. (1982), Young (1983), Krasnopolsky (1986, 2006), Carlson (2010) and Zhang et al. (2012).

Though we cannot distinguish between possible absorbers on the base of photometric analysis alone, preliminary consideration of the phase functions of clouds in the UV dark and bright regions observed in one of the VEx orbits revealed an important role of variations of the refractive index of submicron particles in producing these contrasts. In our previous study, where the data of the only one orbit for UV dark and bright regions were analyzed, we found that the contrasts in the mottled and spotty clouds at low latitudes are caused by different portions of absorbing submicron particles in the clouds, while the droplets of the 1-μm mode are the same in these regions (Petrova et al., 2015). Now, we apply the method suggested in that paper to the other orbits in which UV dark and bright regions were observed by VMC at small phase angles. First, we present the data considered and shortly introduce the technique used in our analysis. Then, the phase functions of brightness (so called phase profiles) of small cloud regions observed by VMC in UV (0.365 μm) and NIR1 (0.965 μm) channels are considered, and the properties of particles in these regions are derived from the comparison of the UV and NIR1 profiles and fitting them with the models. The set of the models was considerably enlarged, especially for UV, as compared to our previous analysis. In a separate section, the phase dependences of brightness of the regions near the long UV-bright bands, that are very often seen at ≈50°S, in the so-called transition region from mottled clouds at lower latitudes to quasi-laminar flow at higher latitudes, are analyzed. The paper concludes with a discussion of the obtained results.

2. Observational data, method, and model parameters

2.1. Data

VMC is a wide angle camera that images the planet in four narrow-band filters centered at 0.365, 0.513, 0.965 and 1.010 μm (Markiewicz et al., 2007a). They share the same CCD. An overview of the data obtained since 2006 and a detailed description of in-flight characterization and calibration of VMC are given by Titov et al. (2012) and Shalygina et al. (2015). Here we consider only the images obtained at small phase angles almost simultaneously in two channels: UV ($\lambda = 0.365$ μm) and near-IR (NIR1, $\lambda = 0.965$ μm). The first channel covers the range of wavelengths of the unknown UV absorber and shows an extremely variable pattern on the cloud top of Venus, while in the second one the cloud blanket of the planet looks mostly featureless and homogeneous.

As has been already mentioned, the glory feature observed by VMC at small phase angles in a number of orbits gave us an