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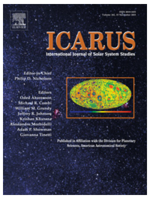

Aerosol properties in the upper clouds of Venus from glory observations by the Venus Monitoring Camera (*Venus Express* mission)

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ABSTRACT

From the angular positions of the glory features observed on the upper cloud deck of Venus in three VMC channels (at 0.365, 0.513, and 0.965 µm), the dominating sizes of cloud particles and their refractive indices have been retrieved, and their spatial and temporal variations have been analyzed. For this, the phase profiles of brightness were compared to the single-scattering phase functions of particles of different sizes, since diffuse multiple scattering in the clouds does not move the angular positions of the glory, which is produced by the single scattering by cloud particles, but only makes them less pronounced. We presented the measured phase profiles in two ways: they were built for individual images and for individual small regions observed in series of successive images. The analysis of the data of both types has yielded consistent results. The presently retrieved radii of cloud particle average approximately 1.0–1.2 µm (though some values reach 1.4 µm) and demonstrate a variable pattern versus latitude and local solar time (LST). The decrease of particle sizes at high latitudes (down to 0.6 µm at 60°S) earlier found from the 0.965-µm and partly 0.365-µm data has been definitely confirmed in the analysis of the data of all three channels considered. To obtain the consistent estimates of particle sizes from the UV glory maximum and minimum positions, we have to vary the effective variance of the particle sizes, while it was fixed constant in our previous studies. The twofold increase of this parameter (from 0.07 to 0.14) diminishes the estimates of particle sizes by 10–15%, while the effect on the retrieved refractive index is negligible. The obtained estimates of the refractive index are more or less uniformly distributed over the covered latitude and LST ranges, and most of them are higher than those of concentrated sulfuric acid solution. This confirms our previous result obtained only at 0.965 µm, and now we may state that the cases of a relatively high real part of the refractive index are often observed for the 1-µm mode of cloud particles on Venus. Consequently, an additional component with a high value of the refractive index is required to be present in the cloud droplets. We suggest that this component is in small submicron particles; during the condensation process, they become incorporated into sulfuric acid droplets, which results in forming the complex UV absorbing particles with an increased refractive index. We suppose that this material can be ferric chloride that is one of the candidates for the so-called unknown UV absorber in the upper clouds of Venus.

1. Introduction

Physical processes in the Venus clouds, completely enshrouding the planet, are driven by the solar radiation energy mainly absorbed in the upper cloud layer. Precise knowledge of the sizes and nature of aerosol particles composing this layer is required for studying the radiative energy balance of the planet and, therefore, understanding the origin of the atmospheric superrotation on Venus, one of the mysteries of the Solar System.

The first reliable estimates of the sizes and composition of particles in the upper clouds of Venus were obtained from the ground-based polarimetry by Hansen and Hovenier (1974). From the phase dependence of polarization, they determined the shape of cloud particles (spherical), their size distribution (the modified gamma distribution with the effective radius $R_{\mathrm{eff}} = 1.05 \pm 0.10\,\mu\mathrm{m}$ and the effective variance $\nu_{\mathrm{eff}} = 0.07 \pm 0.02$), and the real part of the refractive index (1.44 corresponding to concentrated sulfuric acid at a wavelength $\lambda = 0.55\,\mu\mathrm{m}$). According to the later measurements with the particle size spectrometer onboard the *Pioneer*

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Venus probe, which revealed the multimodal size distribution of particles in the Venus clouds (Knollenberg and Hunten, 1980), the particles detected in the groundbased polarimetry were labeled as mode 2. They seem to be present mixed in varying proportions throughout the cloud deck with small submicron particles termed mode 1; a distinct so-called mode 3 of larger particles (more than 3 µm in radius) was identified in the lower clouds (e.g., Ragent et al., 1985; Grinspoon et al., 1993). Observations with the orbital polarimeter during the *Pioneer Venus* mission showed the presence of the upper haze in the polar regions and allowed the radius of haze particles to be estimated at $R_{\mathrm{eff}} = 0.23 \pm 0.04$ µm with the effective variance $\nu_{\mathrm{eff}} = 0.18 \pm 0.10$ (Kawabata et al., 1980; Knibbe et al., 1997; Braak et al., 2002); they were also labeled as mode 1. A more detailed analysis of these data revealed substantial spatial and temporal variations of these parameters (Sato et al., 1996). The photochemical processes providing the sulfuric-acid composition of the cloud aerosols was explained by Krasnopolsky and Pollack (1994). In-situ measurements carried out by the decent probes of the *Venera 9–12, Pioneer Venus*, and *Vega 1–2* missions yielded the data on the vertical structure of clouds and the size distribution of particles below 65 km (see, e.g., Esposito et al., 1983; Ragent et al., 1985 for a review). The atmospheric structure of Venus was further investigated by the *Venera 15* and *16* orbiters and during the *Galileo* flyby (e.g., Zasova et al., 2007). The main clouds lie approximately between 48 and 70 km and are stratified in three layers; their total optical depth exceeds 20. In the upper cloud layer, which is remotely sensed by photometry and polarimetry in the visible spectral range, the size distribution of particles was found to be bimodal with the mean radii around 0.2 and 1.0–1.2 µm (Ragent et al., 1985; Grinspoon et al., 1993).

In the visible spectral range, the upper clouds look homogeneous, while they show considerable contrasts (up to 30%) in UV (Esposito, 1980; Pollack et al., 1980; Esposito et al., 1997). Since a source of energy for photochemical reactions in the clouds is provided by the incoming UV radiation, and, moreover, the maximum absorption of solar energy occurs in the 0.35–0.40 µm spectral domain (Pollack et al., 1980; Moroz, 1981), the explanation of the nature of UV features has been a subject of a thorough analysis for many years (see, e.g., Mills et al. (2007) for a review). Nevertheless, the nature of one of the materials absorbing UV radiation and responsible for the contrasts observed at 0.365 µm is still under discussion (Krasnoplosky, 2016a; 2016b).

For more than eight years (2006–2014) the *Venus Express* (*VEx*) spacecraft successfully operated in orbit around Venus, and a powerful suite of the remote-sensing instruments provided an enormous amount of new data on the properties of clouds and hazes of the planet. From the atmospheric extinction profiles measured in the SPICAV/SOIR occultation experiment, the vertical profiles of sizes and number density of particles in the haze above 70 km were retrieved and their spatial and temporal variability was studied (Wilquet et al., 2009; Luginin et al., 2016). It was found that not only a small mode of 0.1–0.3 µm in radius, but also a larger mode with the radii varying from approximately 0.4 to 1.0 µm may be present in the upper haze. Preliminary analysis of the near-infrared polarization measurements performed with the SPICAV instrument in nadir yielded the estimates of the sizes and refractive index of aerosol particles at a level of the cloud top (Rossi et al., 2015), and they are consistent with the results of the ground-based polarimetry (Hansen and Hovenier, 1974). The results of the SPICAV polarimetry also showed the increase in the amount of small submicron particles in the haze above the clouds at high latitudes.

One more instrument that was designed for investigating the clouds (and, partly, the surface) of Venus in the *VEx* mission is the Venus Monitoring Camera (VMC). It acquired a large amount of wide-angle images of the planet in four narrow spectral bands centered at 0.365, 0.513, 0.965, and 1.01 µm (Markiewicz et al., 2007a; Shalygina et al., 2015), which allowed the knowledge on morphology and dynamics of the cloud deck of Venus to be substantially extended (Markiewicz et al., 2007b; Titov et al., 2012; Khatuntsev et al., 2013). Moreover, the first images of a full glory in unpolarized light on the upper cloud deck of Venus were obtained with VMC (Markiewicz et al., 2014). Glory is an optical phenomenon observed near opposition that poses stringent constraints on the properties of cloud particles: they are to be spherical, and their size distribution is to be rather narrow. From the angular position of the glory features at specified wavelengths, the dominant size of scattering particles may be inferred. To use the potential of the analysis of the phase dependence of the Venus clouds at small phase angles, special VMC observations under such geometry were organized. However, due to technical difficulties (the main of which was probable overheating of some units directly exposed to the Sun, when the spacecraft was turned to observe in opposition), the number of such observations is relatively small. In the UV channel, the glory pattern was observed in less than 90 from more than 3000 orbits of the *VEx* mission. The number of the orbits, when glory was seen in the visible or near-IR channels, is even smaller, since sometimes one or two channels were excluded from the observational sequence. After that the observations in the remaining channels were spaced by shorter time intervals, and, consequently, the phase dependence of brightness in prioritized channels was more accurately monitored.

In our earlier papers devoted to the analysis of the phase dependence of brightness of the Venus clouds, we considered the VMC data acquired to October 2012 mostly at 0.965 µm and partly at 0.365 µm (Markiewicz et al., 2014; Shalygina et al., 2015; Petrova et al., 2015a; 2015b). These studies yielded the effective radius of cloud particles ranging from 1.0 to 1.4 µm for different regions of the cloud deck (the effective variance was assumed to be 0.07), which corresponds to the 1-µm mode of the Venus clouds (the so-called mode 2, see above). It was also found that the sizes of particles in the upper clouds often decrease with increasing latitude: from $R_{\mathrm{eff}} = 1.05$–1.2 to 0.8–0.9 µm at ∼35°S and ∼60°S, respectively, while R_{eff} may sometimes reach 1.5 µm in the equatorial region. At a wavelength of 0.965 µm, the shape of the glory feature in the phase curve turned out to be rather sensitive to the refractive index of particles, which allowed the latter to be also estimated. In some cases it was found to be unexpectedly higher than that corresponding to concentrated sulfuric acid, which requires an admixture of some substance with a high value of the real part of the refractive index. We supposed that this material can be ferric chloride or sulfur; both are also candidates for the unknown UV absorber in the upper clouds of Venus. We suggested that this component is in the small submicron particles that are ubiquitous in the Venus clouds and, under proper conditions, can participate in the condensation of sulfuric acid droplets in the clouds and form the complex UV absorbing particles with an increased refractive index.

Though in our previous phase-function analysis of the VMC data we performed a complete modeling procedure starting from the single-scattering simulations for specified particles to the radiative-transfer calculations for an optically thick medium of such particles under specified observational geometry, our main estimates of the sizes of scattering particles were actually based on the angular positions of the glory minimum α_{min} and/or maximum α_{max}, which are independent of the optical thickness of the cloud layer. Diffuse multiple scattering in the clouds simply makes the glory features, which are produced in the single scattering by spheres, less pronounced, but their angular positions remain to be fixed as determined by the dominating sizes of particles in the layer (see, e.g., Hansen and Travis (1974), Mishchenko et al. (2006), and Petrova et al. (2015a)). In Fig. 1 we directly compare the models of the brightness of clouds calculated with the radiative