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Glory on Venus and selection among the unknown UV absorbers

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ABSTRACT

The comparison of the phase profiles of glories observed on the cloud top of Venus by the Venus Monitoring Camera (*Venus Express*) and the light-scattering characteristics of sulfuric acid droplets, containing admixtures with a high refractive index, makes it easier to choose between some candidates for the so-called unknown UV absorber in the Venus clouds. Since among the candidates there are materials wetted and not wetted by sulfuric acid, we analyze whether small submicron particles adhered to or embedded into the 1-µm H_2SO_4 droplets may actually change the glory pattern normally produced by homogeneous spherical particles and what the conditions are, under which the composite particles formed in heterogeneous nucleation may still produce a glory feature. We have found that one of the most frequently considered candidates, sulfur, can hardly be responsible for the contrasts observed at 0.365 µm on the upper clouds, since it is not wetted by sulfuric acid and submicron sulfur particles, serving as condensation nuclei for sulfuric acid, can only adhere to the H_2SO_4 droplets rather than be enveloped by them. Such droplets decorated by sulfur blobs substantially distort the glory feature characteristic of the scattering by spherical particles or even smooth it at all, while a glory pattern is practically always seen in the images of Venus taken at small phase angles. At the same time, the grains of the other UV absorbers that can be embedded in H_2SO_4 droplets, e.g., the widely discussed ferric chloride, pose no problem in terms of interpretation of the observations of glory.

1. Introduction

Images of Venus taken in the ultraviolet spectral range show a variable blotchy pattern. The observed contrasts (up to 30%) are due to some ultraviolet-absorbing substance that is non-uniformly distributed through the clouds. Sulphur dioxide, which was definitely detected in spectroscopic observations, behaves in this way; however, its spectrum can partially explain the absorption only between 0.2 and 0.32 µm, and some other material must be also contributing to the absorption at longer blue wavelengths. Since the incoming UV radiation is a source of energy for photochemical reactions in the clouds, and, moreover, the solar energy is most strongly absorbed in the 0.35–0.40 µm spectral range (Pollack et al., 1980; Moroz, 1981), explaining the UV features on the upper clouds of Venus has been a purpose of many studies (see, e.g., Esposito et al. (1997) and Mills et al. (2007) for a review). Nevertheless, the nature of the material responsible for the contrasts observed at 0.365 µm is still under discussion (Krasnopolsky (2016, 2017) and references therein).

The images taken in the UV channel of the Venus Monitoring Camera (VMC) onboard the *Venus Express* orbiter showed remarkable variability in the brightness and morphology of the cloud deck of Venus (Markiewicz et al., 2007); however, it is evident that the unknown UV absorber cannot be directly identified from them. At the same time, the VMC measurements carried out at 0.365, 0.513 and 0.965 µm at small phase angles made it possible to estimate not only the effective radius of cloud particles R_{eff}, but also the real part of the refractive index m_{r} (Markiewicz et al., 2014, 2018; Petrova et al., 2015a, 2015b; Shalygina et al., 2015). It should be stressed that this analysis was successful only due to the observations near opposition, where the scattering at droplets, composing the clouds, produces the phenomenon of glory. A glory pattern was observed by VMC each time the images were taken at small phase angles. Recently, from the observations of glory by the UV Imager (the *Akatsuki* mission), the estimates of sizes of the cloud aerosols consistent with the results of the VMC data analysis were also obtained (Lee et al., 2017). Moreover, the glory feature on the upper clouds of Venus was also detected in polarimetric experiments (Hansen and Hovenier, 1974; Kawabata et al., 1980; Rossi et al., 2015). The presence of glory itself poses stringent constraints on the properties of particles that dominate the scattering in the clouds: they have to be spherical, and it is their size that mainly determines the angular position of the glory feature (e.g., Laven, 2005 and references therein). The effect of the refractive index of particles on the glory position is noticeably weaker, but it may change the glory shape, depending on the particles' sizes

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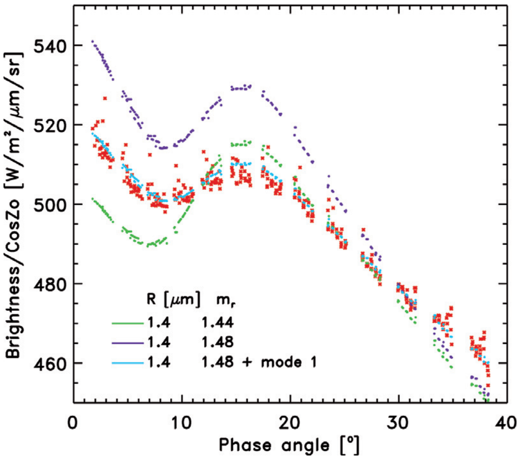

Fig. 1. The phase profile of the brightness coefficient (sets of red dots) measured in the NIR1 VMC channel (0.965 μm) is compared to the models calculated for the cloud layer composed of spherical particles with different real parts of the refractive index m_r; the optical thickness is 30. $R_{eff} = 1.4$ μm with the effective variance $\nu_{eff} = 0.07$. The model, containing the particles of mode 1 ($R_{eff} = 0.23$, $\nu_{eff} = 0.18$, $m_r = 1.44$) homogeneously mixed with those of mode 2 under proportion of 99:1 in number, is also shown. The region of 2° × 2° was observed in the successive images taken during orbit #2481 at different phase angles (near equator, around noon). The points in the measured and model profiles correspond to small regions of 0.2° × 0.2° within that of 2° × 2°. Each close group of dots in the profiles corresponds to a single image of the region. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

relative to the wavelength (e.g., Markiewicz et al., 2018 and references therein).

In many cases, the values of the real part of the refractive index of the 1-μm mode of cloud particles (the so-called mode 2) obtained from the VMC phase profiles turned out to be somewhat higher (by 2–3%) than those characteristic of concentrated sulfuric acid under the conditions in the upper clouds of Venus — 1.43–1.44, 1.44–1.45, and 1.46–1.48 (depending on concentration) for 0.990, 0.548, and 0.364 μm, respectively (Palmer and Willams, 1975). The peculiar behavior of the phase profiles that led us to such a conclusion is shown in Fig. 1 by the example of the VMC profile obtained at 0.965 μm and the radiative-transfer (RT) models calculated for the observational geometry of the observed region (the RT procedure described by Mishchenko and Travis (1997) was used). In the measured phase profile, the surge of brightness toward opposition (the phase angle $\alpha = 0°$) is higher than the glory maximum at $\alpha \approx 16°$. This effect cannot be reproduced either by the model with $m_r = 1.44$, corresponding to the sulfuric acid solution, or by changing the particle sizes and the optical thickness of clouds. Small submicron particles added into the clouds (or above them) only make the profile slope gentler (see also Markiewicz et al., 2014, 2018; Petrova et al., 2015a, 2015b; Shalygina et al., 2015). It is a larger value of the refractive index that may help us to make the surge toward zero phase higher. It should be mentioned that the pronounced enhancement of brightness toward $\alpha = 0°$ (higher than the glory maximum) was observed only in the visible and near-IR channels of VMC, and the light-scattering models show that the glory shape is much less sensitive to the value of the refractive index at 0.365 μm than at longer wavelengths for the particle sizes typical for the Venus upper clouds (see also Figs. 3–5 below and Markiewicz et al. (2018)).

Though the polarimetry-based values of m_r correspond to sulfuric acid, (Hansen and Hovenier, 1974; Rossi et al., 2015), the difference in polarimetric and photometric estimates of m_r, e.g., 1.43 ± 0.015 versus 1.48 in near-IR (as well as in the particle radii, 1.05 μm retrieved from polarimetry versus 1.4 μm in the example shown in Fig. 1), may be explained by the fact that polarization measurements sound somewhat higher atmospheric levels. It is worth mentioning that the values of m_r obtained for the particles of mode 2 from nephelometry on the *Venera* and *Pioneer Venus* probes vary from 1.44 to 1.55 (Ragent and Blamont, 1980; Ragent et al., 1985).

As was noted in our previous papers cited above (e.g., Petrova et al., 2015a), the effect of temperature on the refractive index (Beyer et al., 1996; Biermann et al., 2000) is too weak for the temperature range of the upper clouds of Venus: it results in 2% increase of m_r for the temperature drop from 300 to 200 K. Another way of increasing the effective refractive index of the solution is to introduce an impurity of a high refractive index into the droplets. Such a scenario seems quite probable, since small submicron particles (the so-called mode 1, the effective radius varies around 0.2–0.3 μm) are ubiquitous in the Venus clouds and hazes (e.g., Kawabata et al., 1980; Ragent et al., 1985; Grinspoon et al., 1993; Luginin et al., 2016) and can serve as condensation nuclei for H_2SO_4 droplets. The nature of submicron particles in the clouds is not clear yet, and it likely varies with altitude (Ragent et al., 1985). Moreover, as the fitting of the UV phase profiles by RT models showed, some portion of small submicron particles in the clouds should absorb in UV (Petrova et al., 2015a, 2015b). Consequently, it is natural to think of the UV-absorbing materials among probable candidates with a high refractive index that they may be contaminants in the complex particles formed in condensation of sulfuric acid.

Ferric chloride and sulfur are very frequently discussed as the unknown UV absorber (see, e.g., Mills et al. (2007) for review). In the microphysics and vertical transport models of the clouds and upper haze of Venus, nucleation of photochemically produced sulfuric acid onto submicron polysulfur particles is considered as an essential component (e.g., Imamura and Hashimoto, 2001; Gao et al., 2014; Parkinson et al., 2015). Since sulfur cannot be wetted by sulfuric acid (Young, 1983), it is meant in these models that sulfuric acid condenses on a surface fraction of a polysulfur particle, so that the actual particles would be made up of a polysulfur small particle stuck to the side of the H_2SO_4 droplet (Gao et al., 2014). From the point of microphysics, such a scenario may successfully work; however, from the point of interpretation of photometric and polarimetric observations of the Venus clouds at small phase angles, it poses a problem, since the irregular surface of composite particles may break the conditions for producing glory (Laven, 2005).

Our previous attempts to estimate the influence of the admixture with a high refractive index on the single-scattering phase function of H_2SO_4 droplets were based on a simple two-layer model of spherical particles (Petrova et al., 2015a). Recently, Mishchenko and Dlugach (2012) and Dlugach and Mishchenko (2015) showed that the effect of placing small absorbing grains randomly on the surfaces of larger spherical hosts, as well as imbedding such particles inside the hosts, can be to change the integral scattering and absorption characteristics and the phase function of the hosts quite substantially. The purpose of this study is to analyze whether small submicron particles of a high refractive index adhered to the 1-μm H_2SO_4 droplets or enveloped by the H_2SO_4 solution may actually change the glory pattern normally produced by homogeneous spherical particles at the wavelengths from the near-UV to near-IR and what the conditions are, under which the composite particles formed in heterogeneous nucleation may still produce a glory feature.

2. Modeling

Though the Venus atmosphere is optically thick, the glory feature produced by single scattering of cloud particles survives diffuse multiple scattering in the clouds (see, e.g., Hansen and Hovenier, 1974; Mishchenko et al., 2006; Markiewicz et al., 2018;