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Venus cloud properties inferred from limb darkening curves

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Abstract

The limb darkening (LD) curve is the plot of radiance *I* as function of cosine of the emission angle θ (i.e. angle between the line of sight and the normal to the target). Its shape is related to atmospheric and cloud properties, such as opacity and scale height. These can be deduced also considering the plot of brightness temperature *T* as function of $\cos\theta$ at some wavelengths [1,2]. In this work, Venus clouds have been studied by means of a LD study on infrared images of the Venus nightside, provided by the VIRTIS-Venus Express instrument [3].

1. Introduction

The Radiative Transfer Equation can be approximated by a first-order expansion of radiance as function of the cosine of emergence angle (i.e. the Eddington approximation):

$$I_\lambda(\tau, \cos\theta) = a_\lambda(\tau) + b_\lambda(\tau)\cos\theta \tag{1}$$

where I_λ is the radiance emitted at the wavelength λ and τ is the optical depth. The two parameters *a* and *b* have a physical meaning: *b* is the derivative of *I* with respect to $\cos\theta$, while the sum of *a* and *b* gives the radiance I_0 that would be observed in a Nadir observation. The Eddington approximation gives results with a good accuracy (i.e. order of 1%) only if particular conditions are met [4]. On Venus, these conditions occur at wavelengths lower than 2.6 μm and for $\cos\theta$ higher than 0.4. However, it has been verified that the linear approximation reproduces well the data also in the spectral range 3-5 μm for $0.4 \leq \cos\theta \leq 0.9$ [5].

In the latter spectral interval, the following relation is also valid [1]:

$$T = T_0 + C\ln\cos\theta \tag{2}$$

where T_0 is the brightness temperature in a Nadir observation and *C* is the product of cloud scale height *H* times the upper clouds lapse rate Γ.

2. Data selection and analysis

1725 cube-images from the infrared channel of VIRTIS-M, the mapping spectrometer of VIRTIS, were considered for our study. These images cover the whole Venus nightside within the latitudes 0° and -70°. By means of a statistical analysis of these images, the coefficients of the Eqs (1) and (2) were retrieved for different wavelengths, latitudes and optical depths.

The selected wavelengths are characterised by emission coming from surface (1.03 μm), atmosphere below the cloud deck (1.31 and 1.74 μm), lower haze below the cloud deck (2.30 μm) and upper clouds (3.72 and 4.00 μm) [5,6].

Since it is expected that cloud properties change with latitude, the LD study at each wavelength was performed by selecting different latitude intervals: -40° to 0° (where cloud properties are expected to be homogeneous [2,7,8]), -50° to -40°, -60° to -50° and -70° to -60°.

At a given wavelength and latitude, the parameters of Eqs (1) and (2) have been calculated for ten different optical depth intervals, empirically defined [9].

3. Results and conclusions

3.1 Limb darkening curves

For the same wavelength and latitude range, I_0 (the radiance) and b (its decrease rate with $\cos\theta$) have the same dependence on τ.

At the same wavelength, the LD curves are similar in the latitude ranges -40° to 0° and -50° to -40°, suggesting constant cloud optical properties between the Equator and -50°. Our results are in agreement with LD curves found by means of the analysis of NIMS-Galileo observations [5,10].

Comparing I_0 below -50° and at near-equatorial latitudes, it is observed that: a) I_0 is lower at the wavelengths where clouds significantly affect the emission; b) I_0 remains constant at 1.03 and 1.31 μm. This suggests that the cloud opacity increases at these latitudes, while atmospheric CO_2 absorption remains constant.

Furthermore, b decreases towards the pole at every wavelength. This is consistent with increasing density of the largest cloud particles (i.e. the mode 3 population) at these latitudes [7]. In turn, radiation is more scattered and re-distributed at all the emission angles. The LD curve hence is flatter, i.e. b is lower.

3.2 Cloud scale height

The application of Eq. (2) at 3.72 and 4.00 μm and the assumption of the upper cloud lapse rate of the Venus International Reference Atmosphere [11] allow the retrieval of upper clouds brightness temperature and scale height at different latitudes.

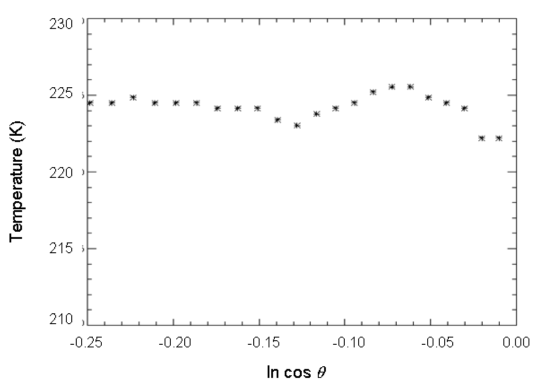

Figure 1: Brightness temperature as function of ln $(\cos\theta)$ at latitudes between -70° and -60°.

T_0 is in the range from 231 to 238 K at near-equatorial latitudes, and on average decreases poleward, according to the cloud opacity increase.

H is about 4 km between the Equator and -50°, independently on the optical depth. This result is in agreement with literature [2,7,8]. From -70° to -60° the fits between T and $\ln(\cos\theta)$ are very poor (Fig. 1), and we ascribe this to a very low value of H (not higher than 1 km), which causes the failure of the linear relation. This result agrees with [8] and disagrees with [7]. The region between -60° and -50° is a transition region, but in average the inferred H value is closer to 4 km than to 1 km, in agreement with [7].

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