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Directional reflectance of optically dense planetary atmosphere illuminated by solar light: An approximate solution and its verification

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ABSTRACT

A new combined approach to calculate the spectral directional reflectance of optically thick cloudy atmosphere illuminated by solar light is suggested. First of all, the approximate method based on the idea of previously developed two-step procedure and a set of 1-D solutions is employed to calculate the local bi-directional reflectance of the cloud layer. After that, the Monte Carlo ray-tracing procedure is used to determine the reflectance of the planet as a whole in the case of a remote sensing from a space vehicle at large distances from the planet. This combined approach appeared to be applicable for planets with opaque cloudy atmosphere. A comparison with the reference Monte Carlo simulation of the complete problem in a wide range of volumetric optical parameters typical of Venus atmosphere in the visible and infrared spectral ranges confirmed very good accuracy of suggested approach. It is recommended to consider the solution obtained as an alternative multi-wavelength method in navigation systems of space vehicles.

1. Introduction

The present paper is concerned with scattering of solar radiation by optically dense planetary atmosphere observed from a large distance from the planet when the visible angular diameter of the planet is small and one can neglect the difference between the directions of light beams coming from various parts of the atmosphere. For simplicity, the optical properties of the external part of a spherical cloud layer are assumed to be uniform. This enable us to focus on the method of calculations, but the method developed can be generalized to the case of a nonuniform atmosphere.

The atmosphere of Venus seems to be appropriate for the use of the method suggested. Therefore, we consider the simplified model of the Venus upper atmosphere as the case problem. It should be recalled that the orbital flights around the Venus are often used in space missions [1–3]. Therefore, an additional orientation system based on the direction and value of solar radiation flux reflected by Venus may be interesting for the potential use in navigation systems of space vehicles. Note that Venus is much brighter than any other planet in the Earth's sky. It is the third-brightness object in the sky, after the sun and moon. The orientation in space using the light reflected by Venus is a specific engineering problem which is not considered in the paper. The details of the reflection by different parts of the cloudy atmosphere are not important to solve the problem at large distances from the planet, and the main parameters such as the observation angle and the distance from the planet can be estimated on the basis of a relatively simple model of the upper cloudy atmosphere.

The objective of the present work is two-fold: (1) to develop a simplified semi-analytical method for computational prediction of the spectral directional reflection of solar radiation by Venus observed from a large distance and (2) to examine the accuracy of this method in a wide spectral range using the reference Monte Carlo calculations.

The cloudy atmosphere of Venus has been studied by several research groups over the world during many years [4–19]. It appears that the clouds containing mainly droplets of sulfuric acid are not uniform and contain two or even three modes of droplets with radii of 0.1–0.2 µm, 0.8–1 µm and about 3.5 µm [17,18]. In addition, the particle size are 1.5–2 times smaller in the polar regions [16,17]. It would be a separate task to overview the published paper and detailed data for Venus clouds reported there, but it is beyond the scope of the present study focused on the simplified approach which is expected to be useful for the space vehicle orientation based on observation of both the Sun light and its spectral reflection from the Venus. At the same time, a brief analysis of the

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Nomenclature

D	radiation diffusion coefficient
E	function introduced by Eq. (3)
G	irradiation
I	radiation intensity
J	diffuse radiation intensity
q	radiative flux
R	reflectance, radial distance, random number
s	coordinate along the ray
$\vec{u}$	unit vector
z	normal coordinate

Greek symbols

α	absorption coefficient
β	extinction coefficient
γ	observation angle
θ	angle measured from the normal
λ	radiation wavelength
μ	cosine of an angle
$\bar{\mu}$	asymmetry factor of scattering
σ	scattering coefficient
τ	optical thickness
ξ	eigenvalue determined by Eq. (7a)
φ, ψ	orthogonal angular coordinates on the spherical surface of cloud layer
Φ	scattering phase function
ω	scattering albedo

Subscripts and superscripts

0	initial
i	incident
j	reflected
i-h	incident-hemispherical
i-j	bi-directional
n-h	normal-hemispherical
obs	observation
sv	solar radiation at the Venus orbit
tr	transport
v	Venus
λ	spectral

optical properties of sulfuric acid droplets typical of Venus clouds is given below to estimate the range of the problem parameters.

2. Spectral optical properties of sulfuric acid droplets

The data reported by Palmer and Williams [20] for spectral optical properties of H_2SO_4 were used in the calculations. The spectral variation of both index of refraction, n, and index of absorption, κ, in the near-infrared range is shown in Fig. 1. The sulfuric acid is almost transparent in the visible range, whereas the index of absorption increases sharply with the wavelength in the near-infrared (Fig. 1b).

The classical Mie theory for absorption and scattering of light by a homogeneous spherical particle [21–23] is used in the calculations for single droplets. Possible electromagnetic interaction of closely positioned droplets is ignored. The latter assumption is known as the hypothesis of independent scattering [24–26]. According to this widely used approach, each particle is assumed to absorb and scatter the radiation in exactly the same manner as if other particles did not exist. In addition, there is no systematic phase relation between partial waves scattered by individual particles, so that the intensities of the partial waves can be added without regard to phase. In other words, each particle is in the far-field zones of all other particles, and scattering by individual particles is incoherent. The computer code described in [27] was used in all the calculations.

In the present paper, the model problem for uniform optically thick clouds characterized by multiple scattering is considered. As a result, there is no need in absolute values of absorption and scattering parameters and the only physical parameter affects the cloud reflectance. This is the so-called transport albedo of scattering. The word "transport" means that we use the transport approximation of the scattering phase function which is presented as a sum of an isotropic part and a peak in the forward direction [28]. In this approach, the so-called asymmetry factor of scattering, $\bar{\mu}$, is sufficient for reliable radiative transfer calculations [27]. The multiple scattering in a semitransparent optically thick medium is really favorable condition for the use of transport approximation because the details of angular distribution of light intensity in single scattering have a negligible effect on the total cloud reflectance [27–29]. The spectral value of transport albedo of single droplets, ω_{tr}, shown in Fig. 2 is defined as follows:

$$\omega_{tr} = Q_s^{tr}/Q_{tr} \quad Q_{tr} = Q_a + Q_s^{tr} \quad Q_s^{tr} = Q_s(1-\bar{\mu}) \qquad (1)$$

where Q_a and Q_s are the ordinary efficiency factors of absorption and scattering [21,22].

The calculations showed that transport albedo of sulfuric acid droplets is not only extremely large in the visible spectral range, where one can use the value of $\omega_{tr} = 1$ for all the droplets, but ω_{tr} is also rather large in the near-infrared range, excluding the case of very small sub-micron droplets, which optical properties are described by the Rayleigh theory. The resulting large transport albedo of cloud droplets explains the observed high reflectance of solar radiation by the Venus atmosphere.

3. Simplified model for radiative transfer

The known observations confirmed that the reflectance of optically thick cloudy atmosphere like the upper atmosphere of Venus is rather high. It means that scattering of solar light in clouds is much greater than the light absorption and the multiple scattering takes place in the cloud. In the case of Venus-like atmosphere, which is characterized by a vigorous circulation, the super-rotation, and hurricane-force winds [30,31], one can use another important simplification. It is assumed in the present paper that the global cloud layer can be considered as a spherical one and an average angular variation of the atmosphere optical properties is relatively small in arbitrary direction. Strictly speaking, the atmospheric circulation of Venus is rather complex, and includes a big double-vortex structure at the Venus South pole [32], but the overall reflectance at large distances from the planet is expected to be weakly sensitive to these effects. So, it is assumed that good estimates of reflectance of Venus atmosphere can be obtained by accounting for only the radial variation of optical properties in a relatively thin spherically symmetric layer of clouds. Moreover, the clouds are optically dense, and one can consider a set of thin discrete cells formed by a grid of latitude and longitude lines. These thin computational cells are almost flat. Therefore, the 1-D approach for radiative transfer in a single cell at oblique incidence of solar radiation can be considered by neglecting the solar light propagation along the cloud surface. Note that the use of a set of 1-D solutions instead of direct solving the original multi-dimensional problem is not a novelty, and this approach appeared to be sufficiently good in quite different applications [33–35].

The distance from the Sun to the terrestrial planets is much greater than the Sun diameter. Therefore, the sunlight is assumed to be collimated. Of course, the real problem is a spectral one, but mathematical formulation of the spectral radiative transfer prob-