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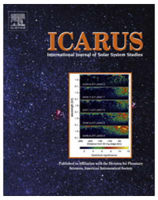

Stratospheric aerosols on Jupiter from Cassini observations

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ABSTRACT

We retrieved global distributions and optical properties of stratospheric aerosols on Jupiter from ground-based NIR spectra and multiple-phase-angle images from Cassini Imaging Science Subsystem (ISS). A high-latitude haze layer is located at ~10–20 mbar, higher than in the middle and low latitudes (~50 mbar). Compact sub-micron particles are mainly located in the low latitudes between 40°S and 25°N with the particle radius between 0.2 and 0.5 μm. The rest of the stratosphere is covered by the particles known as fractal aggregates. In the nominal case with the imaginary part of the UV refractive index 0.02, the fractal aggregates are composed of about a thousand 10-nm-size monomers. The column density of the aerosols at pressure less than 100 mbar ranges from $\sim 10^7$ cm^{-2} at low latitudes to $\sim 10^9$ cm^{-2} at high latitudes. The mass loading of aerosols in the stratosphere is $\sim 10^{-6}$ g cm^{-2} at low latitudes to $\sim 10^{-4}$ g cm^{-2} in the high latitudes. Multiple solutions due to the uncertainty of the imaginary part of the refractive index are discussed. The stratospheric haze optical depths increase from ~0.03 at low latitudes to about a few at high latitudes in the UV wavelength (~0.26 μm), and from ~0.03 at low latitudes to ~0.1 at high latitudes in the NIR wavelength (~0.9 μm).

1. Introduction

Aerosols, or hazes in the stratosphere of Jupiter are of particular interest. First, particular absorbers and scatterers affect the radiative heat budget and the solar energy redistribution in the jovian stratosphere (West et al., 1992; Moreno and Sedano, 1997; Zhang et al., 2013). Second, aerosols are involved in the stratospheric chemical cycle. They are one of the end products of the photochemistry or ion-chemistry (Wong et al., 2003). The haze particles shield the UV light and alter the efficiency of photochemistry in deeper layers. Heterogeneous reactions may occur on the particle surfaces. Third, aerosols can serve as ideal tracers for the stratospheric transport (Friedson et al., 1999) and provide valuable information on the stratospheric dynamics. To evaluate the significance of haze, it is important to determine their latitudinal and vertical distribution and optical properties, such as the optical depth, single scattering albedo, and phase function, for the entire wavelength range from ultraviolet (UV) to the near-infrared (NIR) region.

Taking advantage of the continuum spectra in NIR wavelengths, two attempts have been made to retrieve the global map of haze and clouds on Jupiter. Banfield et al. (1998) retrieved the latitudinal and vertical distributions of stratospheric and tropospheric hazes covering the entire southern hemisphere and northern equatorial region below 25°N. They discovered that a low-latitude haze layer is located at ~50 mbar and its altitude level increases sharply to ~20 mbar in the high latitudes (polar hood). The tropospheric haze top is around 0.2 bar and is non-uniform with latitude. Haze density reaches a minimum in the tropopause region, which is unexpected from the previous models (e.g., Kaye and Strobel, 1983). Recently, Kedziora-Chudczer and Bailey (2011) used a line-by-line multiple scattering radiative transfer model to simulate the NIR spectra with a much higher resolution. Their data cover the entire disk of Jupiter. They assume a 1.3 μm particle layer in the troposphere and a 0.3 μm particle layer in the stratosphere. Their results are generally consistent with Banfield et al. (1998), except for an additional distinct haze layer is discovered around 5 mbar in the polar hoods.

Many studies focused on the aerosol properties in the UV and visible range, from various data sources such as the intensity measurements from spacecraft (e.g., *Pioneer 10* in Tomasko et al., 1978 and *Voyager* in Hord et al., 1979), space-based telescopes (e.g., Tomasko et al., 1986), and ground-based telescopes (e.g., West, 1979), and polarization measurements (e.g., Smith, 1986). Please see the review in West et al. (2004) for details. Generally speaking, the low-latitude aerosols are composed of small particles with radii between 0.2 and 0.5 μm (Tomasko et al., 1986), while the determination of the high-latitude aerosols is more complicated. Some

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studies (e.g., Moreno, 1996; Barrado-Izagirre et al., 2008) assumed small particles (<0.1 μm) to explain the low phase angle images in the polar region, although small particles in fact are not consistent with high phase angle data (Rages et al., 1999). Alternatively, West and Smith (1991) proposed that the high-latitude particles are fractal aggregates in order to reconcile both the positive polarization (Smith, 1986) and the modest forward scattering (e.g., Tomasko et al., 1978). Details such as the monomer radius, the number of monomers, fractal dimension, and refractive index have not been established. One of the purposes in this study is to test this hypothesis for Jupiter and quantify the aerosol properties.

In this study we combine the information from the ground-based NIR spectra and multiple-phase-angle images in UV to NIR wavelengths from the Imaging Science Subsystem (ISS) onboard Cassini during its Jupiter flyby in the late 2000 and early 2001. The ISS acquired ~26,000 high-quality time-lapse images of Jupiter during its 6-months-long flyby from 1 October 2000 to 22 March 2001 (Porco et al., 2003). A proper combination of the images from different filters can be used for a specific purpose. For example, the methane channels and corresponding continuum filters (e.g., MT1/CB1, MT2/CB2, MT3/CB3) provide vertical structure information of the atmospheric aerosols and clouds. The UV1 filter samples the upper troposphere and stratospheric haze layer. Furthermore, Cassini ISS provides images from low to high phase angles. Until now only the low phase angle images have been investigated in the polar region (Barrado-Izagirre et al., 2008). In fact valuable information of the phase functions of the stratospheric particles can be obtained from the high phase angle images, as shown by previous studies, e.g., Tomasko et al. (1978) for the *Pioneer* data and Rages et al. (1999) for the *Galileo* data. Therefore, we analyzed the low, middle and high phase angle images together to characterize the size, shape and phase functions of particles on Jupiter. This method also helps distinguish the compact sub-micron (CSM) particles[1] and fractal aggregates.

This paper is structured as follows. In Section 2 we revisited the data from Banfield et al. (1998) and updated the methane absorption coefficients in the original retrieval model and relaxed the previous assumptions, from which the updated stratospheric aerosol map is obtained. Using a new retrieval model is described in Section 3, the aerosol and cloud properties are retrieved based on the ISS observations, followed by discussions and conclusions in Section 4.

2. Retrieval from NIR spectra

The NIR spectra from Banfield et al. (1998) were taken on August 14 1995, from the 200-in. Hale telescope at Palomar Observatory. The spectra were obtained in broadband *H* (1.45–1.8 μm) and *K* (1.95–2.5 μm) telluric windows, with the spectral resolution power ~100, covering from 25°N to the south pole (~80°S) of Jupiter. Since the stratospheric aerosol optical depth is small in the *H* and *K* bands, Banfield et al. (1996) developed a direct retrieval technique based on the single-scattering approximation for the NIR spectra, under which the radiative transfer inversion problem is linear. Therefore a simple and effective retrieval technique can be applied to minimize the difference between the simulated spectra and the observations in the least-square sense, with a Tikhonov-type regularization term (a two-point Gaussian correlation matrix) in the cost function to smooth the inverted profiles. The retrieval result is called the *f* value, which is defined as (Banfield et al., 1996):

$$f(z) = \frac{1}{4mg} p(\theta)\sigma\omega X(z) \qquad (1)$$

where m is the mean molecular weight of the atmosphere, g is the gravitational acceleration of Jupiter, $p(\theta)$ is the particle phase function at phase angle θ, σ is the particle cross section, ω is the particle single scattering albedo, and $X(z)$ is the volume mixing ratio of particles at altitude z. Therefore, from the NIR spectra we are only able to retrieve the relative abundance of the stratospheric aerosols instead of the absolute values, and even that assumes that the phase function and single scattering albedo do not change with location. Under those assumptions, the vertical shape of $f(z)$ is similar to that of the aerosol volume mixing ratio profile and therefore it can be incorporated into the ISS data retrieval in Section 3. In the entire spectral region, any pixel with reflectivity (I/F) greater than 0.075 was removed to make sure the single scattering approximation is robust. Note that Banfield et al. (1996) assumed the retrieved *f* value is constant with wavelength. Banfield et al. (1998) relaxed the assumption by incorporating the spectral shape of the aerosol extinction efficiency, but still assumed a constant particle size of 0.3 μm with latitude and altitude. See Banfield et al. (1996, 1998) for details of the observations, calibrations and the inverse model.

In this study, we improved the retrieval technique by (1) updating the CH_4 absorption coefficient, and (2) allowing the aerosol size to be varied with latitude. We use the *correlated-k* method to calculate the atmospheric transmission, which is accurate enough for the NIR low-resolution spectra and broadband filters for Cassini ISS images. We adopt the state-of-art CH_4 absorption coefficients from Karkoschka and Tomasko (2010), which are constructed from both visible and NIR CH_4 bands, based on the laboratory data and observed spectra from the Huygens probe on Titan and Hubble Space Telescope observations. The *correlated-k* coefficients are obtained from the calculation by P.G. Irwin (http://www.atm.ox.ac.uk/user/irwin/kdata.html). The upper panel of Fig. 1 shows the total optical depth of CH_4 and H_2–H_2 and H_2–He collisional induced absorption (CIA, based on Borysow and Frommhold, 1989; Bory-

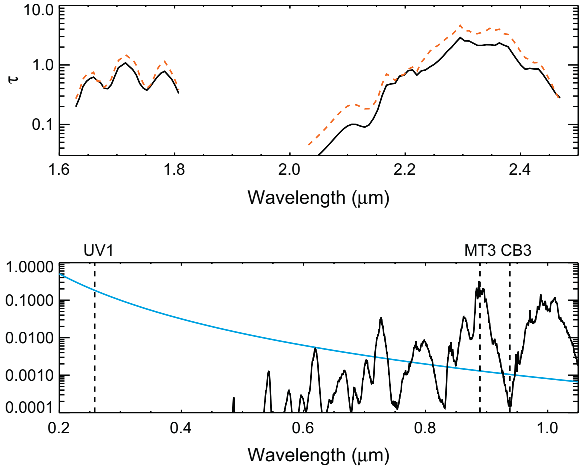

Fig. 1. Total gas optical depth including CH_4 and H_2–H_2 and H_2–He CIA at 100 mbar. Upper panel shows the difference between the results based on the old *correlated-k* coefficients (red dashed line) used in Banfield et al. (1998) and the new data (black solid line) from Karkoschka and Tomasko (2010) for the *H* and *K* bands in the NIR region. Lower panel shows the comparison between the CH_4 optical depth (black) and Rayleigh scattering optical depth (blue) from 0.2 to 1.0 μm. The three vertical dashed lines correspond to the ISS filters used in this study, CB3 (0.938 μm), MT3 (0.889 μm), and UV1 (0.258 μm), respectively. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

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[1] In our study we cannot distinguish spherical and compact non-spherical particles in that size regime and so we use the term "CSM particles". The optical properties of the CSM particles small compared to the wavelength can be calculated using Mie theory even if they are not spheres. This is clearly not true for the fractal aggregates and large crystalline ice cloud particles in the troposphere.