Journal of Quantitative Spectroscopy & Radiative Transfer 210 (2018) 197–203

Contents lists available at ScienceDirect

Journal of Quantitative Spectroscopy & Radiative Transfer

journal homepage: www.elsevier.com/locate/jqsrt

Retrieval of haze properties and HCN concentrations from the three-micron spectrum of Titan

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ARTICLE INFO

Article history:
Received 23 September 2017
Revised 20 February 2018
Accepted 20 February 2018
Available online 22 February 2018

Keywords:
Atmosphere
Infrared
Titan
Haze
Spectroscopy

ABSTRACT

The 3 µm spectrum of Titan contains line emission and absorption as well as a significant haze continuum. The line emission has been previously analyzed in the literature, but that analysis has not properly included the influence of haze on the line emission. We report a new analysis of the 3 µm HCN emission spectrum using radiative transfer equations that include scattering and absorption by molecules and haze particles at altitudes lower than 500 km, where the influence of haze on the emergent spectrum becomes significant. Taking advantage of the dominance of resonant single scattering in the HCN ν_3 fundamental and of the moderate haze optical thickness of the atmosphere around 3 µm, we adopt single dust and molecular scattering and present a formulation for the radiative transfer process. We evaluate the quantitative influence of haze scattering on the emission line intensities, and derive vertically-resolved single scattering albedos of the haze from model fits. We also present the resulting concentrations of HCN for altitudes below 500 km, where we find that the haze scattering significantly influences the retrieval of the concentrations of HCN. We conclude that the formulation we present is useful for the analysis of the HCN line emission from Titan and other similar hazy planetary or celestial objects.

1. Introduction

Extensive observations of the hazy atmosphere of Titan with the Visual and Infrared Mapping Spectrometer (VIMS) on the Cassini spacecraft have produced spectra showing distinctive features in the 0.3–5.1 µm wavelength range, including not only molecular emission and absorption, but also haze scattering and absorption [1–3]. Of these spectral features, Adriani et al. [2] analyzed 3 µm HCN emission spectra that were obtained from dayside limb observations. They only considered high-altitude (>500 km) spectra in which the effects of scattering by haze are minimal. They did not analyze the HCN spectra taken from low altitudes (<500 km), where the influence of haze on the spectra is significant (Figs. 1 and 2 of [2]).

Previously, Geballe et al. [4], Yelle and Griffith [5], Kim et al. [6], and Seo et al. [7] analyzed the emission lines of the 3 µm HCN band in a high-resolution spectrum of Titan obtained at Keck II with the near-infrared echelle spectrograph (NIRSPEC) (Fig. 2). They compared the spectrum with models that included molecular absorption/emission and a partially transmitting cloud or haze layer, but without including vertically-distributed haze scattering/absorption, mainly because at that time the vertical distribution of haze opacity at 3 µm was not quantitatively known.

In this paper, we present a formulation for the radiative transfer equations for Titan in the 2.95−3.15 µm range, which includes the effects of single scattering and absorption by molecules and haze particles, especially focusing on the low altitude (275–500 km) portion of the atmosphere (Fig. 1), where the effect of the haze is significant. We construct synthetic HCN spectra with and without the effects of haze, using the radiative transfer equations, and compare the resulting spectra with the observed spectra from the Cassini/VIMS and Keck II/NIRSPEC observations (Figs. 1 and 2). We discuss the quantitative influence of scattering and absorption by the haze on the observed HCN emission intensities and on the derived HCN mixing ratio. We also compare the influence of haze to other uncertainties in the radiative calculations, such as those arising from the use of the 2-stream approximation, the assumptions of single scattering by molecules and haze particles, isotropic scattering by haze particles, and rotational LTE (Local Thermodynamic Equilibrium).

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https://doi.org/10.1016/j.jqsrt.2018.02.024

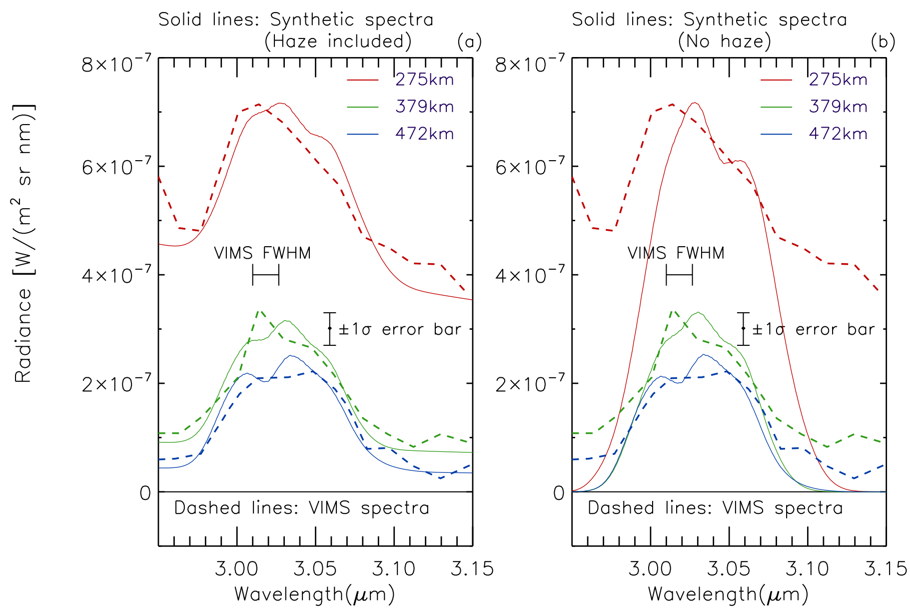

Fig. 1. (a) The VIMS/Cassini limb spectra from Adriani et al. [2], obtained on July 19, 2007 (UT) at latitude 70°S for altitudes z<500 km. Corresponding synthetic spectra including haze scattering and absorption are shown for comparison. The 1σ error is 3×10^{-8} W m^2 nm^{-1} sr^{-1}, the typical VIMS noise level in radiance at 3 µm [2]. (b) The same VIMS spectra as in a, compared with synthetic spectra not including haze scattering and absorption.

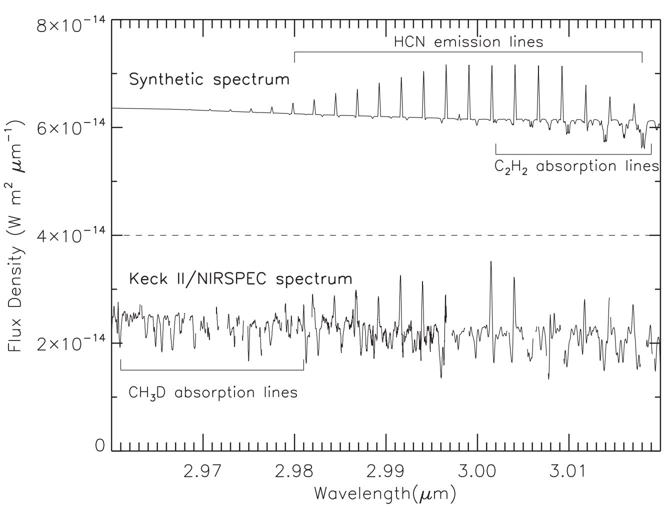

Fig. 2. Lower trace: high-resolution (R ∼ 25,000) spectrum of Titan acquired on November 21, 2001 at the Keck II telescope using NIRSPEC [4]. At the time of the observation, within the NIRSPEC slit the southern hemisphere occupied 70% of Titan's disk. Upper trace: synthetic spectrum, which includes haze scattering and absorption, surface reflection as well as HCN and C_2H_2 fluorescence and absorption. CH_3D absorption lines, which are not included in the model due to their minimal influence, are visible on the left side [7].

2. Radiative transfer formulation including the scattering and absorption of molecules and haze

Radiative transfer in an infinitesimally thin and homogeneous slab of a (planetary) atmosphere considering only isotropic-single scattering and absorption and including thermal radiation by haze particles (e.g., Eq. (129) of [8]; Eqs. (1.2.1), (1.2.11), (4.1.2) of [9]) is described by the equation:

$$\mu dI_\nu/d\tau_{d\nu} = I_\nu - \varpi_{d\nu}J_\nu - (1-\varpi_{d\nu})B_\nu - \varpi_{d\nu}F_{o\nu}\exp(-\tau_{d\nu}/\mu_o)/4\pi\,, \tag{1}$$

where I_ν is the monochromatic radiant intensity; $\tau_{d\nu}$ is given by $(\kappa_\nu+\sigma_\nu)$ndz, where κ_ν and σ_ν are the absorption and scattering coefficients, respectively, both measured in cm^2, n is the number density of haze particles per cm^3, and dz is the infinitesimal altitude in cm; µ is cos θ where θ is the zenith angle of the observer; μ_o is cos θ_o where θ_o is the zenith angle of the sun; $v_{d\nu}=\sigma_\nu/(\sigma_\nu+\kappa_\nu)$ is the single scattering albedo of haze particles; J_ν is the local mean intensity, B_ν is the Plank function; $(1-\varpi_{dv})B_\nu$ is the local thermal radiation from haze particles; and $F_{o\nu}\exp(-\tau_{d\nu}/\mu_o)/4\pi$ is the attenuated sunlight at a certain atmospheric layer. We adopt the geometry for the location of the Cassini spacecraft with respect to Titan and the sun as described in Table 1 of Adriani et al. [2]. In this paper, we assume single scattering by the haze particles, because the haze opacities near 3µm are not very large. Multiple scattering by the haze particles becomes significant in optically-thick atmospheres (e.g., [10–13]).

Similarly, the radiative transfer equation including thermal radiation and fluorescent emission and absorption, and assuming isotropic single scattering by molecules (e.g., Eq. (1.6.16) of [9]), is given by,

$$\mu dI_\nu/d\tau^*_\nu = I_\nu - \varpi^*_\nu J_\nu - (1-\varpi_\nu{}^*)B_\nu - \varpi^*_\nu F_{o\nu}\,\exp(-\tau^*_\nu/\mu_o)/4\pi\,. \tag{2}$$

Here τ^*_ν is the molecular optical depth, $\varpi^*_\nu= A_{ij}/(A_{ij}+N\eta_{ij})$ is the molecular single scattering albedo, where A_{ij} and η_{ij} are the Einstein A coefficient and the collisional deexcitation rate from the i to the j quantum state, respectively, and N is the number density of the atmospheric molecular species being considered. A discussion of the experimental values available in the literature is given in Section 4. In this work, we consider the case of single resonant scattering for the analysis of the 3 µm HCN emission, because the 3 µm emission is dominated by the $\nu_3\rightarrow0$ transition, and the sum of all other 3 µm emissions, such as $2\nu_3\rightarrow\nu_3$, etc., is less than 10% of the $\nu_3\rightarrow0$ emission (see Fig. 7 of [2]). In the cold atmospheres of the outer solar system, the fundamental vibrational transitions ($v=1\rightarrow0$) of molecules dominate over hot band transitions ($v=n+1\rightarrow n$) in most cases.

For an atmosphere containing both haze particles and molecules, the radiative transfer equation for *isotropic* molecular emission and absorption and *isotropic* haze scattering and absorp-