Published in: *Geophysical Research Letters* VOL.25-7 1105–1108, april 1, 1998.

Improved optical properties of the Martian atmospheric dust for radiative transfer calculations in the infrared

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Abstract. A simple synthetic model of the single scattering properties of the atmospheric Martian dust suitable for radiative transfer calculations in the infrared is presented. The model is built by modifying the long-standing Toon et al. [1977] model in order to reproduce accurately the Mariner 9 observations of the 1971 dust storm, without concern to the actual dust composition. Compared to previous Martian dust models which were based on known Earth-analog material, this model should allow more accurate radiative transfer calculations, until new data from the upcoming spacecraft missions becomes available. Integrated values suitable for broad-band climate models are also provided.

1. Introduction

The spacecraft missions of the 1970's have revealed the major role played by the atmospheric dust in the Martian climate. Through their radiative effect, the dust particles strongly influence the meteorology by modifying the temperature structure of the atmosphere, and, in turn, the local and general circulations. Thus, the dust optical properties are of key importance for modeling the Martian environment and interpreting the upcoming Martian data.

At solar wavelengths, several kinds of observations have allowed the estimation of the dust single scattering properties. In particular, measurements of the sky brightness above the Viking Landers have been used to infer the dust single scattering properties at visible wavelength [Pollack et al., 1979, 1995]. These measurements have recently been expanded from ultraviolet to the near infrared by Ockert-Bell et al. [1997], providing a wavelength dependent dust model usable for climate modeling.

In the thermal infrared, the impact of the dust on the radiative transfer through the atmosphere has been observed by the IRIS spectrometer aboard Mariner 9 and the IRTM radiometers aboard Viking. Both instruments have shown that the Martian airborne dust was characterized by a strong silicate induced absorption near 9 μm and a broad continuous absorption beyond 15 μm. On the basis of these observations, several models of the radiative properties of the dust at thermal wavelengths have been proposed in the literature (see below). However, most of them were designed to study the size or the chemical composition of the dust particles rather than their impact on the radiative budget: the basic approach was to assume that the optical indices were described by known Earth mineral or soil type. In this paper, we present a revised set of dust optical properties able to accurately reproduce the key observations (i.e. the IRIS spectra obtained during the 1971-1972 dust storm) and therefore more suitable for radiative transfer calculations. Rather than studying the mineralogy of the dust, our purpose is to provide improved parameters for scientists developing model of the Martian environment or preparing the analysis of the meteorological data from the Mars Global Surveyors and Pathfinder missions.

2. Previous work

Toon et al. [1977] fitted brightness temperatures models to the Mariner 9 IRIS observations (5-50 μm) of the 1971 global dust storm. They showed that the shape of the observed absorption between 8 and 13 μm could be reproduced by using the optical properties of a clay mineral sample called montmorillonite 219b, and a rather large particle size distribution based on a Deirmendjian [1969] modified gamma distribution corresponding to a cross section weighted mean radius r_{eff}=2.75 μm and variance ν_{eff}=0.42. Widely used Pollack et al. [1990]; Haberle et al. [1993]; Wilson and Hamilton [1996], the Toon et al. montmorillonite model has become a kind of standard Martian dust model. However, this model is far from being perfect. In particular, it predicts spurious absorptions at 20 μm [see e.g. Hunt, 1979], in a spectral region where the blackbody emission is close to its maximum at Martian temperatures. To improve this point, Toon et al. suggested to mix the montmorillonite with basalt. However, this leads to a degradation of the fit of the 9-μm band.

An alternative model has been recently proposed by Clancy et al. [1995] to match the complete ultraviolet-to-30-μm absorption properties of the dust. Their model is based on a smaller (r_{eff}=1.8 μm) broader (ν_{eff}=0.8) particle size distribution coupled with the use of the optical properties of a weathering product of basaltic glass called palagonite. Compared to the Toon et al. model, this model is more realistic from the point of view of mineralogy. It substantially improves the fit to the IRIS data, but remains unable to match the 9-μm absorption and the observations beyond 20 μm in details.

3. Data and Methods

Following Clancy et al. [1995] , we have based our analysis on four individual IRIS spectra obtained during the 1971 global dust storm. The four spectra were obtained in the middle of the day, at different locations (See Table 1 in Clancy et al. [1995] for detailed characteristics). They all exhibit a strong dust signature. To study the dust optical properties, we have tried to duplicate this signature with calculated spectra. The spectral signature of the dust particles have been simulated with a radiative transfer program that allows for absorption, scattering, and emission by atmospheric aerosols Toon et al. [1989]. This algorithm is based on the two-stream, hemispheric mean, source function solution to the equation of radiative transfer and allows for the emission angle of the observations. The atmospheric temperature profiles were estimated directly from the CO_2 15-μm band by inverting iteratively the observed radiances using the narrow-band model developed by Hourdin [1992] for Mars. This model does not include the effect of the dust. This effect should be negligible for the upper atmosphere which is sampled by the center of the band where the CO_2 opacity is very strong. In the lower atmosphere, we have limited possible errors by determining the surface temperature from the brightness temperature at 7 μm, where the dust opacity is minimum, and by fitting the temperature profile to the 13 - 15-μm side of the CO_2 band where the dust absorption appeared to be lower. The calculation presented below has been performed assuming a constant dust mixing ratio for the entire atmospheric column. In reality this ratio probably decreased above 50-70 km Anderson and Leovy [1978]. However, a sensivity study performed with different dust vertical distribution have shown that the contribution of the dust lying above 40 km to the outgoing infrared radiance is negligible. As in Toon et al. [1977], we have assumed that the ground emissivity was constant at every wavelength. In fact, significant surface emissivity variations could occur in the dark region of Mars where the albedo is below 0.28 Christensen [1982]. The albedo of the regions where the IRIS spectra were obtained appear to be above this limit, except maybe for spectrum 3 from Solis Planum. Nevertheless, this particular spectrum corresponds to a very strong temperature gradient. In such conditions, the thermal signature from the surface should be small compared to the effect of the dust.

4. An improved dust model

Our purpose being the best parametrization of the Martian dust from a radiative transfer point of view, we have designed a "synthetic" dust model without concern for the actual dust composition. Because the size distribution and

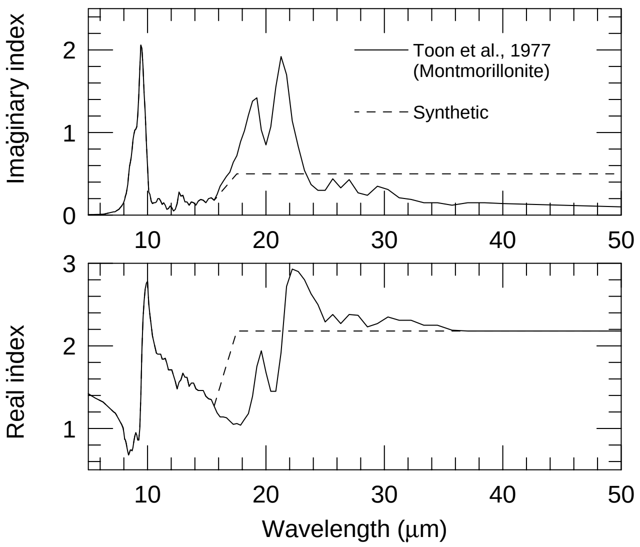

Figure 1. Refractives indexes of our "synthetic" model compared to the Toon et al. [1977] montmorillonite.

the optical properties suggested by Toon et al. were able to closely match the observed 8 - 13-μm absorption band, we kept this model below 15 μm, and tried to improve it above 15 μm. What had to be improved ? The complex refractive indexes of the Toon et al. montmorillonite 219b are shown in fig. 1. The corresponding single scattering parameters, including the extinction coefficient $Q_{\rm ext}$, the single-scattering albedo ω and the asymmetry parameter g, deduced from the Mie theory are presented in fig. 2. The montmorillonite 219b is characterized by two absorption bands at 19 and 21 μm. Such bands are not apparent in the IRIS spectra of Mars atmospheric dust. In fact, unlike the Si-O stretching fundamental band near 9-10 μm which appears in most silicates, these two bands are not universal. In particular, measurements by Roush et al. [1991] have shown that rock types thought to be close to the Martian rocks (palagonite, saponite) do not exhibit such bands. However, most of these minerals, including montmorillonite, are characterized by a real index of refraction near 2.2 beyond 30 μm.

Based on these considerations, we have tried to reproduce the IRIS observations just by fixing the real index at 2.18 (the montmorillonite real index in the far infrared) above 17 μm. The amount of atmospheric dust (characterized by the vertical dust optical depth) was estimated for each spectrum by fitting the observed 9 μm band. Following this protocol, we have found that very good results could be obtained for the four spectra with a constant imaginary index of 0.5 over the same spectral region (figs. 1). The corresponding Mie single scattering properties are shown along with the Toon et al. data in figure 2. In reality, it is unlikely that the imaginary index remain exactly constant up to very high wavelengths. According to the Kramer-Kronig dispersion relation, the imaginary index should slightly decrease with wavelength in the very far infrared if the real index is constant. However, since our goal is to determine the single scat-

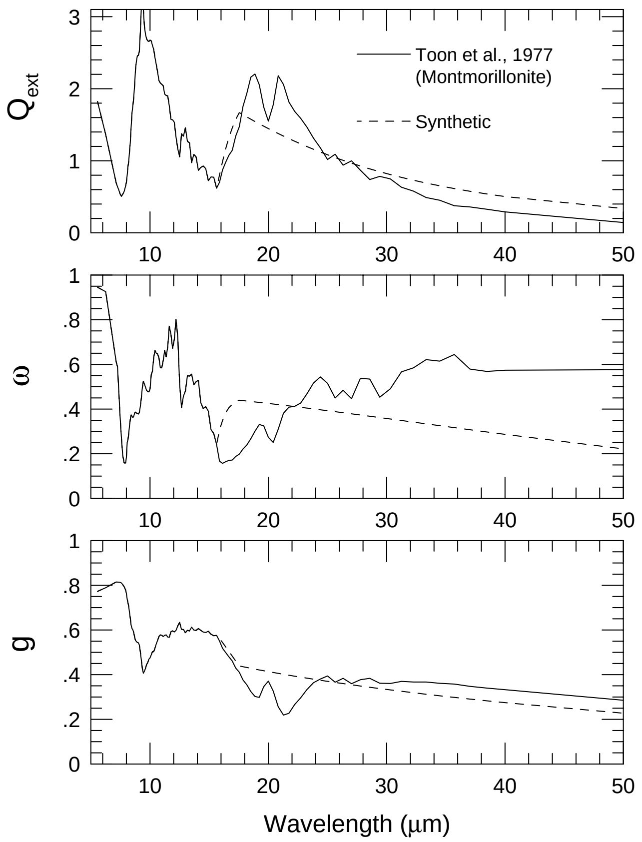

Figure 2. Single scattering properties of our synthetic dust model compared to the Toon et al. [1977] model. Q_{ext} is the extinction parameter, ω the single scattering albedo and g the asymmetry parameter.

tering properties rather than the actual index of refraction a modelled, ideally constant index appear to be satisfactory for our purpose.

The ability of the new dust model to reproduce the observations is shown in figure 3. At any wavelength, the difference between the modeled and observed brightness temperatures is lower than 2 K. The four spectra were fitted using a dust optical depth at 9 μm near 1 (0.92, 1.30, 1.12, 1.05 respectively). Thus, the impact of the scattering by the dust, which mostly depends upon the dust optical depth, is of the same order in the four cases: a brightness temperature decrease by about 5 to 8 K between 20 and 40 μm (based on calculations performed with an isothermal temperature profile). On the opposite, the decrease of radiance due to absorption and emission by dust particles colder than the surface is not the same in the four cases. This is due to the fact that the temperature gradient strongly varies with location and time. For instance, the temperature difference between the surface and the "top" of the emitting atmosphere is about 25 K for spectra 1 and 2, and almost 50 K for spectrum 3, spectrum 4 being in between. The fact that our dust model is able to accurately fit the four spectra in spite of these differences is worth emphasizing. In two cases (spectra 1 and 2), the dust signature is dominated by scattering, with a strong constraint on real index, and in an other case (spectrum 3), by absorption, with a strong constraint on the imaginary index. A counter-example is provided by the Toon et al. montmorillonite model beyond 30 μm. The agreement is good in the scattering cases (spectra 1 and 2), whereas the model strongly overestimate the brightness temperatures in the absorbing case (spectrum 3), indicating that the imaginary index of montmorillonite is too low in this spectral region.

5. Visible/infrared opacity ratio.

The scaling of the dust opacity in the infrared compared to the visible is a key parameter in the model since it controls the local radiative balance of the atmosphere and a potential dust "greenhouse effect". This scaling is not straightforward. Indeed, the size distributions that are used in scattering calculations are nothing more than model parameters used to average single scattering properties. Since they are deduced by fitting observed radiance on limited spectral regions, the size distributions only constrain the relative weight of the particle size affecting the radiation in these particular spectral regions. Consequently, the relative visible and infrared opacities could strongly differ, depending for instance on the poorly known submicrons size distribution which affects solar wavelengths much more than the infrared Zurek [1982]. Fortunately, it has been possible to derive this key information from separate measurements of the dust optical depth made at both solar and infared wavelengths at the same time and location. Martin [1986] compared his IRTM 9-μm opacity determinations over the two Viking Landers sites with the lander solar extinction observations. He determined a visible (0.67-μm) / 9-μm opacity ratio of 2.5. More recently, a value of about 2 has been supported by separate analyses of the

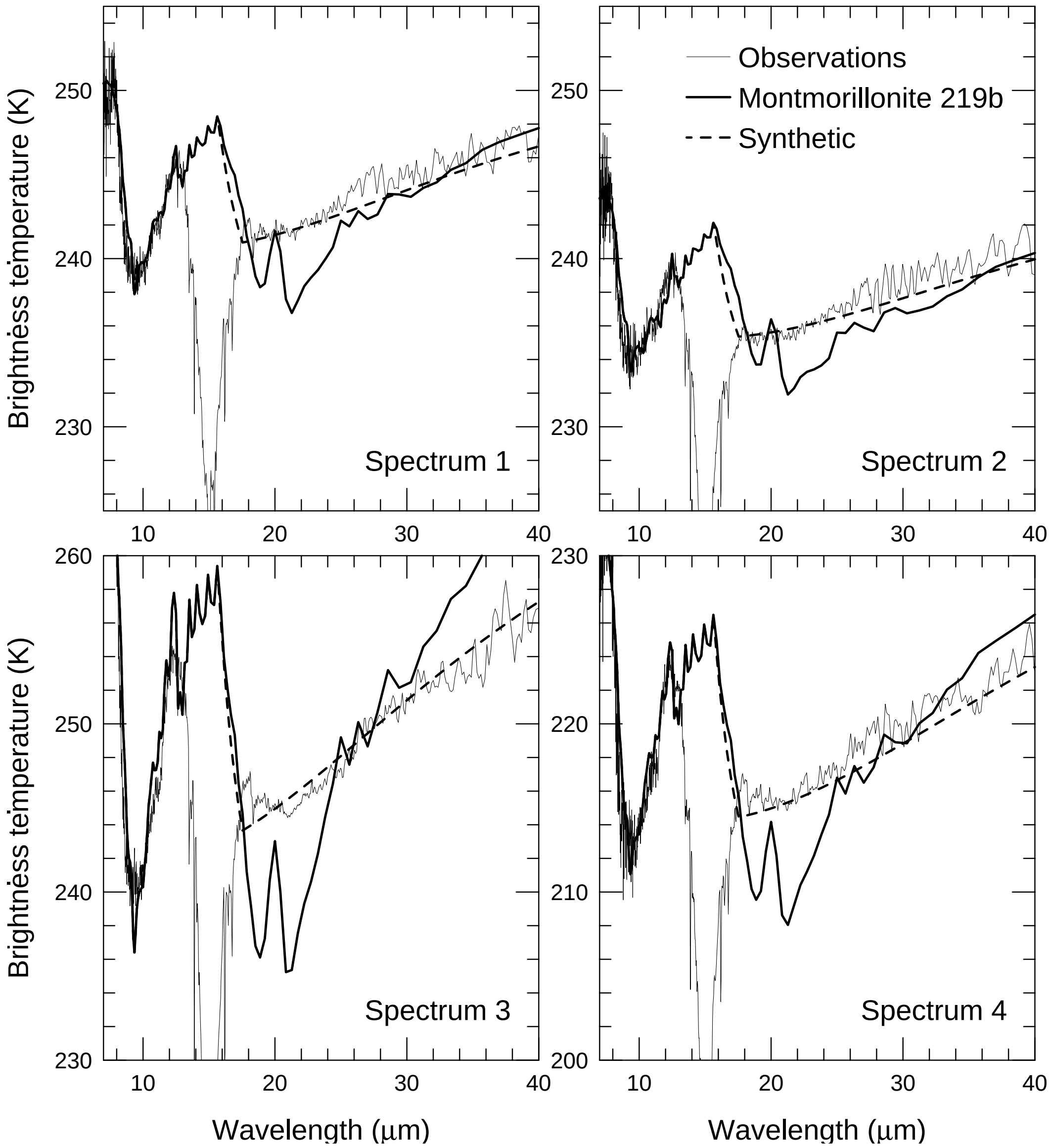

Figure 3. Comparison between four "dusty" IRIS spectra and modeled spectra computed with the Toon et al. [1977] model and our new synthetic model.

IRTM emission-phase-function visible and 9-μm sequences Clancy et al. [1995], with an apparent tendancy to increase with higher dust opacities, which could explained the discrepancy with Martin's results. In these studies, the "9-μm" opacity corresponds to a mean opacity averaged over the 8-10 μm band of the IRTM instrument. However, according to our dust model this mean opacity appears to be coincidentally very close to the exact opacity at 9-μm. Overall, until more accurate data are made available, we would recommend to use $\tau_{0.67\mu m}/\tau_{9\mu m} = 2$ in atmospheric modelling studies.

6. Integrated scattering parameters

Many atmospheric models, and in particular tridimensional general circulation models, require rapid calculations for the radiative transfer in the infrared Pollack et al. [1990]; Haberle et al. [1993]; Wilson and Hamilton [1996]. Such models cannot afford multispectral calculations, and usually only use one or several broad spectral bands with averaged optical properties. For instance, the dust model presented in this paper is now used in the Martian General circulation Models developped at the Laboratoire de Météorologie Dynamique in France Hourdin et al. [1995] and at the Atmospheric Oceanic and Planetary physics department of the Clarendon Laboratory (Oxford University) Collins et al. [1996], with four wide spectral bands in the thermal infrared. The averaging of the extinction and absorbing coefficient Q_{ext} and Q_{abs}, of the single-scattering albedo ω and asymetry parameter g is done as follow :

$$\tilde{Q}_{\mathrm{ext}} = \frac{\int_{\lambda_1}^{\lambda_2} B_\lambda Q_{ext,\lambda}\, d\lambda}{\int_{\lambda_1}^{\lambda_2} B_\lambda\, d\lambda} \qquad \tilde{\omega} = \frac{\int_{\lambda_1}^{\lambda_2} B_\lambda Q_{\mathrm{ext},\lambda}\omega_\lambda\, d\lambda}{\int_{\lambda_1}^{\lambda_2} B_\lambda Q_{\mathrm{ext},\lambda}\, d\lambda}$$

$$\tilde{g} = \frac{\int_{\lambda_1}^{\lambda_2} B_\lambda Q_{\mathrm{ext},\lambda}\omega_\lambda g_\lambda\, d\lambda}{\int_{\lambda_1}^{\lambda_2} B_\lambda Q_{\mathrm{ext},\lambda}\omega_\lambda\, d\lambda}$$

where B_λ is the Plank fuction at a mean temperature and λ_1, λ_2 the wavelengths at the boundaries of the band. For the entire thermal infrared spectrum, and with a mean Martian temperature of 215 K, we obtain mean values $\tilde{Q}_{\mathrm{ext}} = 1.16$, $\tilde{\omega} = 0.45$ and $\tilde{g} = 0.49$. Assuming a visible to infrared ratio $\tau_{0.67\mu m}/\tau_{9\mu m} = 2$, that leads for instance to a mean dust infrared extinction optical depth $\tilde{\tau}_{\mathrm{IR}} = 0.24 \times \tau_{0.67\mu m}$.

Acknowledgments.

I am grateful to Richard Fournier for his help and his suggestions. Further thanks are extended to Frédéric Hourdin and Olivier Talagrand. This work was supported by the European Space Agency through ESTEC TRP contract 11369/95/NL/JG.

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July 18, 1997; accepted December 12, 1997.

This preprint was prepared with AGU's LaTeX macros v4, with the extension package 'AGU^{++}' by P. W. Daly, version 1.5g from 1998/09/14.