Infrared Optical Constants of Martian Dust Derived from Martian Spectra.

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Introduction: The infrared optical constants of the aerosol dust on Mars have been of interest for several decades [1, 2]. They are useful for several modeling tasks, including atmospheric heat balance, extracting the surface spectrum through a dusty atmosphere, and modeling dust/ice mixtures in the Martian polar caps. Accurate optical constants can also aid the understanding of the composition of the dust. Until recently, Martian aerosol spectra have been fit only with modeled laboratory spectra of terrestrial analogs [1, 2]. My interests have been modeling the spectral effects of a dusty atmosphere over a surface and the mixture of dust and ice in the polar caps. For these purposes, optical constants which best fit the measured spectra are desired.

For example, when the optical constants of Martian dust from Clancy et al. [2] (derived from laboratory measurements of terrestrial palagonite) were used in models of dusty CO₂ ice, poor fits to polar spectra in the 20–50 µm region resulted [3]. Model dust optical properties that are based on spectra of Mars aerosols have been obtained recently (using both Mariner 9 infrared spectra [4] and Mars Global Surveyor (MGS) Thermal Emission Spectrometer (TES) spectra [5]). I am pursuing an independent study of the infrared dust signature in the Mariner 9 spectra with particular emphasis on the high precision results necessary for the analysis of high spectral resolution data. Model optical constants from analysis of a single spectral average assuming a blackbody underlying surface has been completed [6], and is described below. This model included a sensitivity study of inherent dust opacity and dust particle size distribution. Using these optical constants, fits to polar ice spectra are greatly improved.

However, ignoring surface emissivity may lead to errors in the derived shape of the absorption bands, and using only one spectrum ignores possible and probable variations in the dust properties, especially with large dust amounts in the atmosphere. This may be important, because the goal is to provide properties for typical or average dust. The solution is to analyze a fair number of averages with different surface and atmospheric temperatures and different dust loadings in the same way (but with streamlined processing). The only restriction on these spectra is that they are acquired only over significantly dust-covered surfaces on the planet according to MGS TES data [7]. This is so that the model is simplified to a dusty atmosphere over a dust-covered surface, both with the same optical properties. I anticipate that the resulting surface spectra will be qualitatively and possibly quantitatively consistent with the derived surface spectra of dusty regions on Mars from MGS TES [8, 9]. Inspection of these averages indicates that some differences in dust optical properties may be necessary to fit them well.

Early Modeling: We prefer using spectra from the Mariner 9 infrared interferometer spectrometer (IRIS) [10] over the much more numerous spectra from MGS TES because of the higher spectral resolution that allows one to easily discern the signatures of atmospheric gas in the spectra. We are confining ourselves to the thermal infrared wavelengths longer than ~8 µm, where the dust both absorbs strongly and scatters light. One of the properties of this data set is that the bulk of the observations were recorded during the decay of a global dust storm, and are not necessarily characteristic of the typically small dust optical depths.

The spectra we selected for our initial fitting were from near the end the prime mission on Rev 172, with a low dust optical depth that is only a few times larger than the typical background amount. Five IRIS spectra were averaged to improve signal-to-noise. A smoothed dust signature was derived from the spectrum by estimating the strength of atmospheric bands, including the CO₂ "hot" bands in the region around 10 µm, using a clear atmosphere band model [11] (Figure 1). The shape seen here is quite similar to the spectrum derived from TES data presented in Figure 2 of Smith et al. [12].

Then trial optical constants were entered into a forward model which included (1) the real index of refraction calculated from a trial imaginary index using a
subtractive Kramers-Kronig process (setting the visible index to 1.45), (2) Mie calculations for spherical particles and size distributions consistent with current estimates [e.g., 13, 14] (non-spherical particle shape is mostly inconsequential at these wavelengths), (3) an atmospheric model with well-mixed dust and a temperature structure based on an inversion of the 15-µm CO$_2$ band [15], and (4) a multiple-stream plane-parallel multiple scattering radiative model [16] using a blackbody for the surface. The imaginary indices were varied until the dust signature was closely approximated. This typically was done using a scaled model-to-smoothed-spectrum ratio to modify the imaginary index and converged in 5-10 steps.

**Sensitivity to free parameters.** Even though this is a limited model, it was possible to easily investigate the effects of free parameters and other uncertainties on the problem. In particular the inherent dust opacity is a completely free parameter, since little is known about the number density of dust particles in the atmosphere. The total optical depth, which can be estimated, is a product of the particle optical depth and the number density and can be matched to any particle opacity by choosing the appropriate number density. Therefore, the peak imaginary index at the top of the 9-µm band was varied over about half an order of magnitude (0.4–1.25), the optical depth was adjusted to match the smoothed spectrum at 9 µm, and the optical constants were adjusted at all other wavelengths to match the rest of the spectrum. The resulting optical constants are plotted in Figure 2.

Another major uncertainty is size distribution of the dust particles. This has been estimated at various wavelengths (mostly visible to near infrared) in several papers; I have catalogued 23 size distributions from 10 publications. The effective radius of the particles in these models ranges from 0.7 to 2.8 µm. The distributions can easily be grouped into seven clusters which fully describe the variation in spectral behavior. For each of the seven size distributions, the imaginary index at 9 µm was set to 0.85, and the index at the other wavelengths was adjusted to fit the smooth spectrum, as before. The resulting optical constants for this study are plotted in Figure 3.

**Results and conclusions.** This sensitivity study implies that we need to apply some constraints on the opacity and size distribution to improve the usefulness of any average optical constants that are derived. The variation of the 9-µm band strength is somewhat physically constrained. Scaling it up and down results in non-proportional changes to the 20-µm bands to retain the match to the IRIS spectra. The measured 9-µm imaginary index for basalt, andesite, and basaltic glass is between 1.1 and 1.2 [17], while montmorillonite and
granite are in the range 1.7–2.1 [1]. It seems unlikely that a physically reasonable material can have this value much greater than 2 or less than a few tenths (where the Snook et al. [3] model is), with the most likely value near 1. Raising the 9-µm and 20-µm band strengths yields an increasing long-wavelength real index ($n_\infty$) through the Kramers-Kroenig integral. The infinite wavelength real index is equal to the square root of the DC dielectric constant, $\varepsilon$. $\varepsilon$ falls in the range 4–10 for many minerals and somewhat higher (10–25) for well crystallized materials such as basalt or granite. The bulk dielectric constant of Martian dust is unlikely to be much larger than 10, implying an upper limit for the $n_\infty$ of about 3. If we choose the model with 9-µm imaginary index of 0.85 (very similar to that of palagonite used in the Clancy et al. [2] dust model) and the central size distribution, it has $n_\infty$ of about 2.1. The reasonable range defined by this constraint is a 9-µm strength from about 0.7 to 1.0 and a size distribution from small to medium large. Figure 4 compares these new models to previous models and results. The lattice absorptions at $\lambda$>20 µm need to be much broader than those of palagonite to match the Mars spectra. The width and position of the 9-µm band is also different from palagonite.

**Refinement of the optical constants and the scope of their variation:** As described in the introduction, we have looked for IRIS spectral averages over dust covered surfaces with a wide range of surface and atmospheric temperatures, including at night. The resulting data includes 93 average spectra. An attempt to achieve greater automation in the processing has been undertaken. The chief problem encountered is the difficulty of converging on a good fit in the most transparent regions of the dust spectrum. Here, the surface spectrum is sensitive to transparency in the opposite sense to the aerosols, resulting in almost no change in the model result when the absorption is increased or decreased in those regions. This is also a function of the surface temperature, which is now a less constrained parameter compared to the early blackbody models,
where it was fixed by some part of the spectrum. The current best fit of the first of the 93 spectra is shown in Figure 5. Notice the considerable misfit in the same regions where the surface emissivity is low. A solution to this problem is forthcoming. The optical constants for this exercise are compared to the chosen model from the earlier work in Figure 6. The greatest changes occur in the transparent regions, but there are subtle changes in the shape and position of the absorption bands, as well. Since these wavelength regions are well and easily fit, this implies some variation in the dust properties.