A RADIATIVE TRANSFER MODEL APPLIED TO THE ANALYSIS OF DUST SUSPENDED IN THE MARTIAN ATMOSPHERE.

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Introduction:

The ancient Martian climate was probably very different from the current one, with an annually average surface temperature close to 210 K and an atmospheric pressure of about 6 mbar. However, climatic models suggest the possibility that, in the past, the surface temperature and the atmospheric pressure were high enough to allow a stable presence of liquid water on the surface (Pollack et al., 1987; Forget and Pierrehumbert, 1997; Yung et al., 1997). This hypothesis is supported by remote sensing images of the Martian surface, which show the presence of interesting geomorphic features such as dendritic channels, apparently carved through slow erosion by water running across the surface (Masursky et al., 1977; Malin and Carr, 1999). In this scenario, the recent observations by OMEGA Mars Express, reporting the presence of outcrops rich in kieserite, gypsum, and polyhydrated sulfates (Gendrin et al., 2005), strengthen the hypothesis of an ancient wet Mars. These findings, together with the in situ observations of the two rovers, Spirit and Opportunity, are beginning to change our view of Mars, even if, in order to understand the climatic evolution of the planet it would be important to collect new remote sensing spectral data. In fact a reliable estimate of the total amount of Martian evaporites, important for assessing the issue of the past existence of liquid water on the planet, could probably be attempted only after the detection of these minerals in the Martian aerosol.

It is very difficult to obtain reliable information about the mineralogy of the Martian surface or aerosol dust, comparing directly laboratory and remote sensing data, especially in the thermal range. The interpretation of spectral remote sensing data is not straightforward because observed spectra are the results of a combination of different contributions: thermal emission from the surface, transmission and emission of atmospheric gases, aerosol particles, and water-ice clouds. In this respect, we wish to stress that it is important to use a correct approach for analysing remote sensing data taking into full account the radiative process due to the presence of a complex atmosphere. In addition such evaluation process can be very useful for discriminating between surface and atmospheric dust contribution and, altogether, for a better understanding of the Martian atmosphere.

Many different approaches have been developed in order to extract useful and reliable information from the great amount of observational data. In this context, our approach to the interpretation of the Martian spectra is based on a careful comparison of the observational data with synthetic spectra produced by means of an appropriate radiation transfer model, using laboratory data on dust particles. In the simulation of the total radiance the cumulative effects of the surface, as well as the atmospheric gases and dust, have been taken into account.

Model:

Different methods have been developed for the analysis of the observed Martian spectra in order to derive the mineralogical composition of surface or aerosol. Some authors compare directly the observational data, properly reduced, with laboratory spectra specifically measured [Blaney and McCord, 1989; Calvin et al., 1994; Marzo et al., 2005] or use laboratory spectra for the discussion of specific observational issues [Wagner and Schade, 1996]; some authors have used ratios of different regions [Pollack et al., 1990; Roush, 1995; Moersch et al., 1997], or different techniques based on the use of algorithms for the separation of spectral features caused by atmospheric and surface components [Smith et al., 2000]. In many cases, however, the comparison is done using synthetic spectra, calculated by means of reliable codes, in order to reproduce the observed spectra [Blecka, 1999; Lellouch et al., 2000; Federova et al., 2002], and also our approach is based on a simulation of the signal detected.

Our method for the interpretation of the Martian spectra is based on a careful comparison of the observational data with synthetic spectra produced by means of an appropriate radiation transfer model, based on the spectral properties of convenient materials measured in laboratory under controlled conditions. The radiative transfer model used for the simulation of Martian spectra is the MODTRAN code (version 3.7). MODTRAN (MODerate TRANsmission) is an atmospheric model which allows to calculate the spectral transmittance and radiance for arbitrary atmospheric paths from the microwave through the visible range. Although this code has been originally designed for terrestrial atmosphere, it has been proven surprisingly flexible in coping with the requirements for modeling the influence of the Martian atmosphere.

In our simulations, we focus our attention on the spectral region of the thermal infrared, where the spectral features of many interesting materials are present. In this spectral region observed spectra are greatly influenced by the absorption, transmission, scattering and emission of the gases and dust. These processes depend on the nature and relative abundances of gases, on the vertical profile of temperature and pressure, on the composition of the aerosol particulate, on the shape and size of dust and water ice grains. Martian dust is composed mainly of small particles with radii much smaller than the wavelength, at least in the thermal region of the spectrum and during quiet atmospheric conditions, and for such particles scattering becomes unimportant [Blecka, 1999; Smith et al., 2001].

Therefore, in order to compute the total radiance, the input parameters for the modelling are: atmospheric temperature and pressure profile, concentration of gases, number density and optical parameters of dust and water-ice, temperature and emissivity of the surface, spectral range and observation geometry. The great advantage of using this radiative transfer model is that it takes into account, in the simulation of the total radiance, the cumulative effects of all components, but it is possible to model separately each component, allowing a better understanding of their contribution to the observed spectra.

Procedure:

In this work, we have basically simulated the influence of Martian dust on two TES spectra acquired with a high emission angle in order to reduce the influence of the surface (fig. 1). Infrared remote sensing spectra are usually provided as radiance, but it is useful to convert spectral radiance into emissivity, or brightness temperature, for enhancing small features and removing temperature effects.

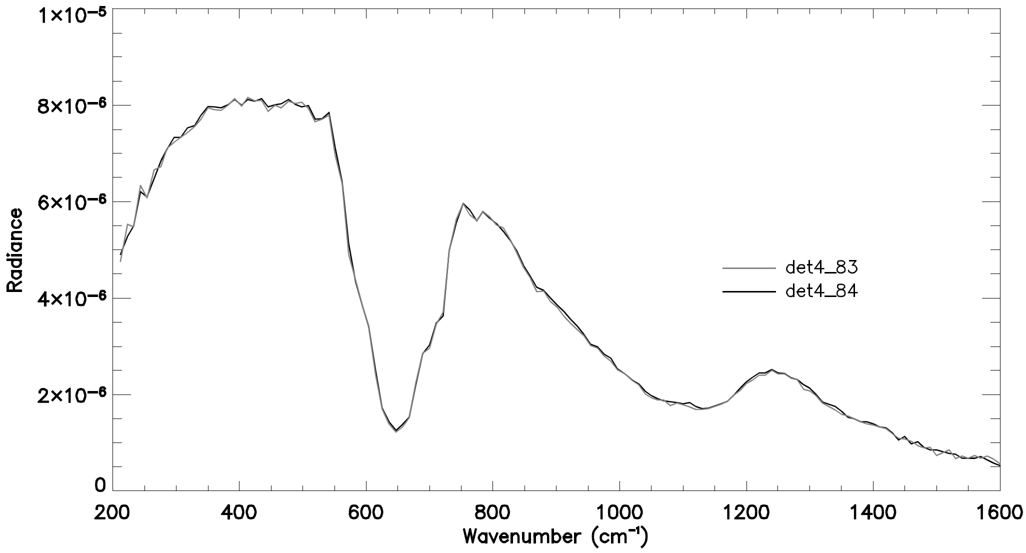

Fig 1. Two TES spectra observed with a high emission angle, respectively, of 83° and 84° by detectors 4 and 5, and in similar atmospheric conditions.

The following step is to calculate a synthetic spectrum for an atmosphere free of dust and clouds and in the same observation geometry: in this way it is possible to take into account only the influence of the atmospheric gases. This synthetic spectrum has been calculated supposing an atmosphere made only of CO_2 (95.3 %) and H_2O (0.05 %), after having checked that removing the other minor components did not cause any appreciable change in the synthetic spectrum.

In order to carefully model the atmosphere it is necessary to define the appropriate vertical thermal profile, which is usually derived by fitting the main 15 μm (~ 670 cm^{-1}) CO_2 band, above the observed location. For the two selected spectra it is obviously impossible to use such procedure due to the observation geometry. The approximation we adopted in this case is to retrieve the necessary thermal profile, using an average of nadir spectra taken in similar physical conditions and close to the observed location.

The ratio between the average of the two observed spectra and the synthetic one, calculated including only the gas contribution, is shown in fig. 2. The resulting spectrum evidences the strong absorption due to dust and, at first glance, it does not exhibit major contribution due to water ice clouds.

After having considered the gaseous component of the Martian atmosphere, in order to reproduce also the influence of the Martian dust, we must introduce in the MODTRAN code the optical properties of suspended particles. These properties, as accepted by the code, are the extinction and absorption efficiencies (Q_{ext} and Q_{abs}) and these spectral quantities can be derived either from laboratory transmittance spectra (in some approximations: spherical particles much smaller than wavelength, thus $Q_{ext} \approx Q_{abs}$) or from the optical constants. In any case, preliminary assumptions about the nature of the particulate present in the Martian atmosphere are needed.

Results:

After various tests, we have chosen a mixture of basalt (54 %), basaltic glass (20 %), gypsum, (21 %), and very small percentages of calcite (4 %) and quartz (1 %), which fits the bands of the ratioed spectrum better than other combinations previously considered. The match between the transmittance spectrum of the chosen mixture and the ratioed spectrum is shown in fig. 2. It could be easily seen that the agreement is rather poor and this is only partially due to the residue influence of the strong CO_2 band. The main point is that the depth of the main dust band is very difficult to reproduce by means of laboratory transmittance measurements, due to the numerous radiative processes which occur in the Martian atmosphere. In other words the ratioed spectrum can not be regarded as a transmittance spectrum. It follows also, from this comparison, the importance of using a radiation transfer model in order to include all the matter-radiation interactions before

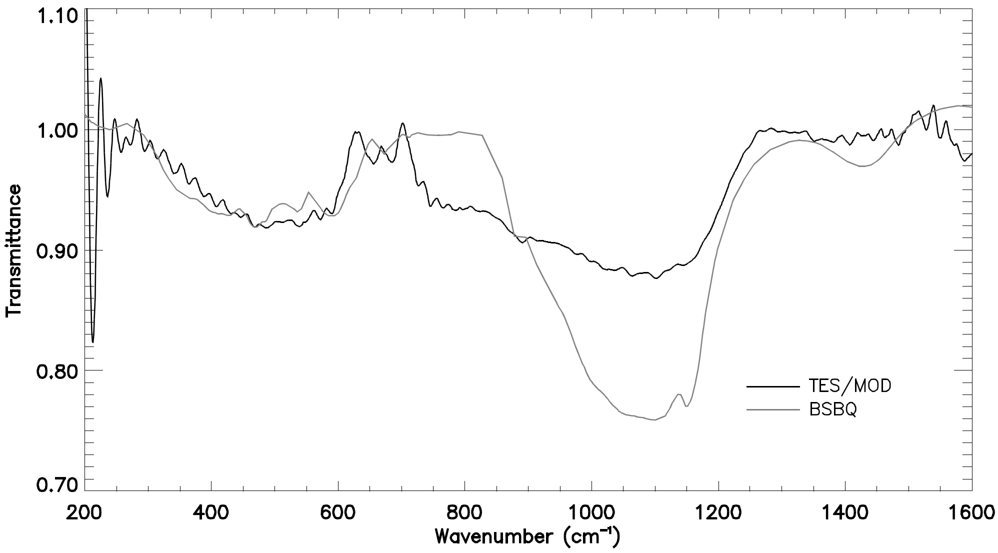

Fig 2. Comparison between the dust spectral shape, as derived from calculations (TES/MOD), and the transmittance spectrum of a mixture composed of basalt, gypsum, basaltic glass, calcite and quartz (LAB MIX).

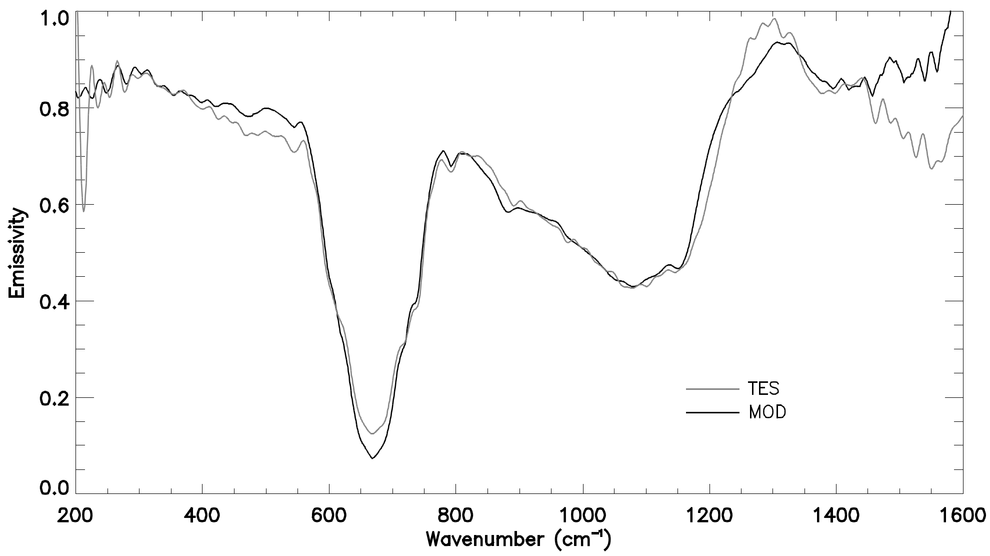

Fig 3. Comparison between the TES spectrum (TES), average of the spectra shown in fig. 1, converted into emissivity, and the synthetic spectrum calculated with MODTRAN (MOD), in the same geometry of the observed spectrum, for an atmosphere with the same gas content of the spectrum shown in fig. 2 and the dust content described by the mixture composed of basalt, gypsum, basaltic glass, calcite and quartz, discussed in the text. The presence of clouds is not considered in these calculations.

any quantitative spectral comparison. The proper comparison between the observed and the modelled spectrum, obtained by feeding the chosen dust properties into the radiation transfer model, is shown in fig. 3.

The agreement between the two spectra is certainly much better than in fig. 2 even if some differences still occur and will be widely discussed in the presentation, together with the choice of the mixture components. In fact we are fully aware that, while basalt and basaltic glass are among the most widely accepted components of the Martian regolith and aerosol, gypsum, calcite and quartz have seldom been proposed.

We wish to stress, however that gypsum, calcite, and quartz have to be taken simply as representative of mineral classes, such as sulphates, carbonates, and silicon dioxides and have been chosen only as the most widely studied representative of each group. In fact, in our view, it is not appropriate trying to fit spectra recorded with a high emission angle with specific minerals, since the observed spectra should be basically related to the average composition of the dust suspended in the Martian atmosphere, with almost no connection to any specific mineral, more conveniently related to particular surface locations.

Finally it is worthwhile to note that, although the chosen mixture can definitely be acceptable, certainly it is not the unique combination able to fit the average of the two selected Martian spectra. Therefore the results presented here need to be validated by means of open discussion and reasoned comparison with other possible solutions. In addition the presented approach and procedure should be considerably improved, in order to account for the remaining discrepancies between observed and synthetic spectra.

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