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**ISO Observations of Mars: An Estimate
of the Water Vapor Vertical Distribution
and the Surface Emissivity**

**M. Burgdorf, Th. Encrenaz, E. Lellouch, H. Feuchtgruber,
G. Davis, B. Swinyard, Th. de Graauw, P. Morris,
S. Sidher, M. Griffin, F. Forget and T. Lim**

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Abstract

Infrared spectra of Mars were taken with the two complementary spectrometers onboard the European Space Agency's Infrared Space Observatory, ISO, both in moderate- and high-resolution mode. From the strengths of the observed water lines we derived information about the vertical distribution of water vapor and on the emissivity of the dust/surface system in the infrared. Assuming atmospheric and surface temperatures derived from the European Martian Climate Database with a slight adjustment to the observed $15\text{ }\mu\text{m}$ CO_2 band, the ISO data are consistent with an H_2O mixing ratio of $(3 \pm 1) \times 10^{-4}$ at the surface, a saturation level at (13 ± 2) km and a total column density of (12 ± 3.5) pr- μm . The mean disk emissivity is found to be close to 1.0 at $6\text{ }\mu\text{m}$ and 0.92 ± 0.02 at $40\text{ }\mu\text{m}$. At longer wavelengths the emissivity decreases from a value of 0.97 ± 0.03 at $50\text{ }\mu\text{m}$ to 0.92 ± 0.03 at $180\text{ }\mu\text{m}$.

Key words: infrared observations; Mars, atmosphere; Mars, surface; spectroscopy

1. Introduction

The water cycle on Mars involves complex processes, which are far from being completely understood presently. Due to seasonal effects, water is transported within the atmosphere from one pole to another; there is also an exchange of water with the clouds and with non-atmospheric reservoirs (polar caps, hydrated surface material). As a result of the various processes involved, the water vapor distribution exhibits strong spatial, seasonal and interannual variations.

After several campaigns of ground-based measurements (Barker 1976; Jakosky and Barker 1984), the water vapor abundance on Mars has been monitored at the time of the Viking space mission by the Mars Atmospheric Water Detection (MAWD) experiment, which measured the H_2O global column density as a function of latitude and season. Largest abundances were measured at high northern latitudes during northern summer ($L_s = 120^\circ$), and were interpreted as water sublimation from a residual H_2O ice polar cap (Jakosky and Farmer 1982; Jakosky and Haberle 1992). There is also a local peak of water vapor abundance at southern latitudes during southern summer, but this maximum is about six times smaller than the northern maximum, which suggests that the southern polar cap never loses its CO_2 frost (Kieffer 1979; James 1979). Since the Viking mission, information upon the H_2O abundance was retrieved from the ISM-PHOBOs space experiment (Rosenqvist *et al.* 1992; Titov *et al.* 1994). In addition, the water vapor abundance on Mars has been systematically monitored through

several campaigns of ground-based measurements, both in the optical range (Rizk *et al.* 1991; Sprague *et al.* 1996; Barker 1997; Sprague *et al.* 1997) and at radio wavelengths (Clancy *et al.* 1992, 1996). The seasonal variations observed during the Viking mission were generally confirmed, but strong variations from one cycle to another were also reported (Jakosky and Haberle 1992; Sprague *et al.* 1996).

An important parameter to understand the water transport is the atmospheric level where saturation takes place, as it controls the H₂O cloud formation. This information can be obtained from the vertical distribution of water vapor, which shows a strong cut-off at the saturation level where condensation takes place. Unfortunately, most of the water measurements obtained up to now were performed in the solar reflected part of the Mars spectrum, at visible or near-infrared wavelengths. As a result, information was retrieved on the total column density of water vapor, but not on its vertical distribution. New observations of Mars in microwave transitions of H₂O (Clancy *et al.* 1992, 1996; Encrenaz *et al.* 1995) and HDO (Encrenaz *et al.* 1991, 1998; Clancy *et al.* 1996), observed with heterodyne spectroscopy at very high resolution ($R = 10^6$), have been successfully used over the past few years to infer some information on the water vapor vertical distribution; however these transitions are weak and difficult to observe.

The Infrared Space Observatory provided a unique opportunity to study the water vertical distribution of Mars through the study of several rotational and ro-vibrational transitions. We report here the analysis of SWS and LWS spectra of Mars, recorded both in the grating and Fabry-Perot (FP) modes. From the analysis of the water vapor lines, we derive the H₂O surface mixing ratio, its

column density and the saturation level. In a second step, we used the inferred H_2O vertical distribution in order to derive information about the disk emissivity from the measured line-to-continuum ratios.

2. The ISO observations

The ISO satellite consisted of a 60-cm helium cooled telescope, in a 24-hour highly elliptical orbit around the Earth. It was launched in November 1995 and ended its life in April 1998 when all helium was lost. A description of the ISO satellite can be found in Kessler *et al.* 1996. During its lifetime, strong observability constraints were imposed to keep the satellite as cold as possible; in particular, observations within 60° from the Sun and from the anti-Sun direction were prohibited. As a consequence, Mars was observable only during a very short period, in July and August 1997.

2.1 SWS

Observations of Mars were performed with the Short Wavelength Spectrometer (SWS) of ISO, both in the grating mode with the Astronomical Observation Template (AOT) S06 ($R = 1000 - 2000$) and in the Fabry-Perot (FP) mode with AOT S07 ($R = 30,000$). A full description of SWS can be found in de Graauw *et al.* 1996. Three grating spectra of Mars were recorded by SWS in July-August 1997 (Morris *et al.* 2000). In this article, we analyse a SWS spectrum recorded on July 31, 1997, from 2.3 to $45\ \mu\text{m}$ in the grating mode, with an aperture of $14 \times 20\ \text{arcsec}^2$ below $12\ \mu\text{m}$ and $14 \times 27\ \text{arcsec}^2$ above $12\ \mu\text{m}$. A preliminary analysis of the 4 - $20\ \mu\text{m}$ region has been published by de Graauw *et al.* 1997. We present

here the 5.6 - 8 μm and the 39 - 41 μm parts of the spectrum, which both exhibit strong absorption lines of water vapor. In addition, four H_2O transitions were observed in the 39 - 41 μm range, between July 29 and August 12, 1997 (Table I). The total integration time was 2.2 hours for the full grating spectrum, and some 40 minutes for each Fabry-Perot scan.

The typical errors in the absolute photometric calibration lie between 5 and 25% for wavelengths below 12 μm ; beyond 26 μm , however, they rise up to 35%.

2.2 LWS

The spectrum of Mars between 45 and 196 μm was measured with the Long Wavelength Spectrometer (LWS) of ISO in grating mode (AOT L01). It provided a resolution of 0.29 μm below 90 μm and of 0.6 μm at longer wavelengths. In addition we used an FP scan with AOT L03 from 61 to 63 μm with a resolution element of 8 nm. The instrument and its calibration are described in Clegg *et al.* 1996, Burgdorf *et al.* 1997 and Swinyard *et al.* 1998.

The grating spectrum presented here was recorded on August 15, 1997 (ISO's revolution no. 639). It differs from all other LWS observations of Mars in that a lower bias voltage was applied to the detectors. As a consequence the number of saturated data points was reduced from several thousand for a comparable spectrum at nominal bias to only 1. The different bias required in the pipeline processing the use of a special relative spectral response function (RSRF) which was derived from a low bias measurement of Uranus. Besides, the bias change modified the absolute detector responsivity by a poorly known multiplicative constant, but this does not influence the line-to-continuum ratios

which are the basis of the results presented in the following, because the responsivity depends for LWS (and SWS) only weakly on the flux level.

The FP-spectrum was not affected by saturation because of its high spectral resolution, but the strong flux of Mars produced straylight in the instrument. If this is not taken off, one ends up with a residual flux of about 20% in the continuum. A special calibration observation was executed in order to measure this background signal. It consisted of an end-to-end grating scan on Mars with the FP in the beam. This way certain wavelengths of the incoming radiation were filtered out with the grating and then actively rejected by the FP, hence providing the true zero level that had to be subtracted from each Mars FP-spectrum. The source of the straylight is not well known at the time of writing. Since it constitutes only a small part of the measured signal, however, its error margin is negligible compared to the overall flux uncertainty with the FP. The LWS Interactive Analysis (LIA) software was used to remove the grating profile from the FP data.

3. The atmospheric model of Mars

At the time of the ISO observations, the angular diameter of Mars was between 6.0 and 6.5 arcsec so that, for all SWS spectral bands (and all the more for the LWS), the Martian disk was fully included in the aperture. On July 31, 1997, the planetocentric orbital longitude L_s of the sun was 157° , which corresponds to the second half of northern summer. The sub-Earth point was at 24° N latitude, so that ISO was mostly seeing the northern hemisphere. About 9/10 of the disk

were illuminated by the Sun, and the observations were executed in the morning (local time).

The shape of the water lines depends on several parameters: the surface brightness temperature T_b which defines the continuum level; the H_2O mixing ratio Q at the surface and the temperature distribution which define the H_2O vertical distribution and thus the depth and the shape of the absorption lines.

Taking into account the seasonal time and the mean latitude of the grating observations, we assumed a mean surface pressure of 5.1 mbar (Zurek 1992). The flux emitted by the surface in the infrared range is the product of the blackbody emission of the surface temperature T_s by the emissivity ϵ , which is unknown and probably wavelength dependent. The surface temperature is very variable over the Martian disk, with maxima as high as 280 K on the day side and minima as low as 160 K in the night side. We used the temperature profile and the surface temperature maps of the Martian Climate Database (MCD, Lewis *et al.* 1999) as a starting point for deriving the disk-average temperature profile. The MCD is based on output of state-of-the-art General Circulation Models (Forget *et al.* 1999; see in here for a discussion of the differences to previous models, e. g. the NASA Ames General Circulation Model, Haberle *et al.* 1993 and Barnes *et al.* 1993). The mean atmospheric temperature profile was then retrieved from a best fit adjustment of the $15\ \mu m$ CO_2 band (Lellouch *et al.* 2000). Even though the observations with ISO were executed at quite different sub-Earth longitudes (see Table I) and consequently at different surface pressures, we only used a single profile with a mean pressure, because the variations in the disk averaged values amounted to less than 1 mbar. The resulting profile is shown in Fig. 1. Assuming, for a given wavelength, a

constant emissivity over the Martian disk, fluxes were integrated geometrically to calculate brightness temperatures as a function of the wavelength (for a more detailed description of the modelling see Encrenaz *et al.* 1995). Calculations were compared to the ISO data in the region of the ν_2 band of H_2O around $6.2\text{ }\mu\text{m}$, in the $39\text{--}41\text{ }\mu\text{m}$ range which exhibits strong rotational transitions of water vapor and in the far infrared between 50 and $180\text{ }\mu\text{m}$. The purpose of the study is (1) to derive the vertical distribution of water vapor and (2) to retrieve information about the emissivity of the Martian disk as a function of wavelength. It has been checked that the presence of dust in the atmosphere has a negligible effect on the retrieval of these parameters. Indeed, assuming that the $7\text{--}12\text{ }\mu\text{m}$ absorption features are entirely due to atmospheric dust, we have calculated the spectra and the H_2O line depths assuming a dust cloud with an optical depth of 0.1 at an altitude of 10 km . The effect of this cloud on the relative (line/continuum) H_2O line depths is found to be very small at 6 and $40\text{ }\mu\text{m}$.

4. Results

4.1 The $5.6\text{--}8\text{ }\mu\text{m}$ range

Figure 2a shows a comparison of the SWS spectrum with a variety of models, corresponding to different mixing ratios of H_2O at the surface. The best fit to the observed spectra is obtained for a ratio $Q = 2.5 \times 10^{-4}$, constant with height (no. 1a in Table II), and for 3×10^{-4} , with saturation (no. 2a). These two models reproduce the observations equally well (Figure 2b). However, we consider

model 2a being physically more realistic, as model 1a would imply supersaturation. An emissivity of 1.0 was used in the calculation. It can be seen that this value provides a good fit of the continuum as a whole, both in its absolute value and in its shape: In all cases, the difference between the models and the SWS data is within the uncertainty of the SWS absolute calibration (lower than 11% at certain key wavelengths). Assuming an emissivity of, for instance, 0.9 would have no significant effect on the derived model atmosphere.

4.2 The 39-41 μm range

4.2.1 The disk emissivity

The absolute calibration of the SWS is least reliable at the long wavelength end, therefore we use the SWS grating data here only for a measurement of the ratio between the flux at the line center and its immediate continuum.

Fig. 3 shows a comparison of the ISO grating data in the 39-41 μm range with 3 atmospheric models calculated with the same atmospheric parameters as model 2a, but with 3 different values of the emissivity (1.0, 0.92 and 0.75). The grating spectrum has been normalized in order to bring it in agreement with the models at the centre of the water lines. It can be noticed that the models show less variations in the centers of the strong H_2O lines than in the continuum. The signal in the core of the strong H_2O lines comes from some atmospheric level where the H_2O abundance is constrained by saturation, and thus, for a given strength of the H_2O line, a corresponding temperature is probed, independent of the temperature profile, the surface mixing ratio of H_2O and the surface emissivity. Because the spectral resolution is not infinite, this is true only at

first approximation, but it can be checked on Fig. 4: For the FP lines, the 3 saturated models give the same value in the core for the 2 strong lines at 39.4 and 40.3 μm . Because water is constrained by saturation, the temperature of the atmospheric layer probed in the H_2O strongest lines is also independent of the atmospheric profile. As a consequence, the relative fluxes measured in the strongest H_2O lines do not strongly depend of the atmospheric and surface parameters. The comparison of the line-to-continuum ratios of strong and weak H_2O lines as measured with the SWS and synthetic spectra between 39 and 41 μm suggests a disk emissivity of 0.92 ± 0.02 in this spectral range.

4.2.2 The water vertical distribution

Fig. 4 (a, b, c, d) shows the 4 H_2O lines observed by ISO-SWS in the Fabry-Perot mode between 39 and 41 μm , compared with a set of 4 synthetic spectra (nos. 1b, 2b, 3 and 4 in Table II). Because of the large uncertainties in the absolute calibration of the ISO data, the observed spectra have been arbitrarily normalized and no flux error is given. For the line-to-continuum ratios discussed here the normalization factor cancels out. (Uncertainties of the relative flux calibration between adjacent points in the spectrum are small compared to the line depths.)

The 2 strongest lines, at 39.4 and 40.3 μm , tend to favor models 2b and 3; it has to be mentioned, however, that the fit of the FP data is far from satisfactory. A possible explanation is some residual instrumental problem which might alter the definition of the continuum of the ISO data. In addition, differences between the fits of the four FP lines might be due to variations of the observational

conditions, e. g. of the altitude level of the sub-Earth point. Our conclusion from the analysis of both the 6 μm and the FP data is that model 2 is favored ($Q = 3 \times 10^{-4}$ at the surface, saturation at 13 km, total H_2O column density of 12 pr- μm). Models 3 and 4 provide a conservative estimate of the upper and lower acceptable values of these parameters. As model 1 implies supersaturation it is regarded as unrealistic, although it is not incompatible with the data.

In conclusion, it is possible to fit the H_2O signatures of the SWS data, both at 6 μm and in the 40 μm region, with a H_2O vertical distribution corresponding to a mixing ratio of $(3 \pm 1) \times 10^{-4}$ at the surface, a saturation level around (13 ± 2) km and a total column density of (12 ± 3.5) pr- μm . The mean surface emissivity of the Martian disk is found to be close to 1.0 at 6 μm and 0.92 at 40 μm .

4.3 The 50-180 μm region

On the basis of the water vertical distribution determined with the SWS we calculated the strengths of the water lines in the far infrared and compared them with the LWS measurements (see Fig. 5). Model spectra were generated for this with three different emissivity values for the surface: 1.00, 0.95 and 0.90. For each of the lines in these spectra we determined then the emissivity as a function of the theoretical line-to-continuum ratio. The relationship between emissivity and line depth is not exactly linear, but the error made in interpolating between the different models is negligible compared to the measurement uncertainties. These functions were then applied to 18 measured lines in the wavelength range from 48 to 180 μm . We assumed in this a Gaussian shape of the lines and used the ISO Spectral Analysis Package (ISAP) to

determine their parameters. The resulting emissivity values are plotted in Fig. 6. We find a slight decrease of emissivity with wavelength around an average value of 0.95. The error bars in the figure were derived from the line fits and include the RSRF errors. Values obtained from different detectors for the same line were averaged. The uncertainties in the water vertical distribution can produce an additional, systematic error in the calculated emissivity values in the order of ± 0.02 .

Figure 7 displays the spectrum of Mars between 61 and 63 μm as measured with the LWS-FP; the lines at 61.8, 62.4 and 62.9 μm were clearly detected. Under the assumption of an Airy function for the line profiles the comparison between modelled and observed line-to-continuum ratios gives here emissivity values of 0.93, 0.93 and 0.90. With the current state of our understanding of the instrument we are not in a position to assign reliable error bars to these numbers. The uncertainty of the FP absolute flux level, however, is 30 percent, therefore it is not possible to determine the emissivity directly from the measured continuum emission (see also Sidher *et al.* 1999, Fig. 5).

As the calibration of the line fluxes is more trustworthy for the grating than for the FP subsystem, we adopt the global value of $\epsilon = 0.95$ for the wavelength range from 50 to 180 μm . Within this range there is a significant decrease from an emissivity of 0.97 ± 0.03 at the short wavelength end to $\epsilon = 0.92 \pm 0.03$ near 180 μm .

5. Discussion

The seasonal and interannual variations of water vapor on Mars have been studied by several authors (Jakosky and Barker 1984; Rizk *et al.* 1991; Jakosky and Haberle 1992; Sprague *et al.* 1996; Barker 1997; Sprague *et al.* 1997), using both ground-based measurements in the visible range and the Viking MAWD data. These analyses provide maps of the water column density as a function of the latitude and the areocentric longitude. Rizk *et al.* 1991, from observations before and after the 1988 opposition, found H₂O abundances in agreement with the Viking results for early southern spring ($L_s = 208^\circ$) and southern autumnal equinox ($L_s = 360^\circ$) but values 2 times higher than the Viking ones for the southern mid and late summer ($L_s = 320^\circ - 340^\circ$). Interannual variations by a factor as high as 3 were reported by Sprague *et al.* 1996 from ground-based monitoring between 1988 and 1995; the seasonal shifts, however, were found comparable to those of Viking. For $L_s = 157^\circ$, the global H₂O column density derived from the Viking observations and averaged over the disk as seen from Earth, is in the range of 10 - 15 pr- μm (Jakosky and Barker 1984). Our value is compatible with the Viking data if we consider the uncertainties.

Clancy *et al.* 1996 have reported a ground-based monitoring of the temperature profile (between 1980 and 1995) and the water vertical distribution (in 1993 - 1995) around Mars aphelion. Their analysis indicates that, at that time of the season and at low to mid-latitudes, the temperature is colder than the Viking values by about 15 - 20 K, and water is confined to altitudes below 10 km. As discussed by Clancy *et al.* 1996, this behavior is observed because Mars aphelion presently coincides to northern late spring/early summer, and northern summer is colder by 20 K than southern summer due to the high eccentricity of the Mars orbit. Microwave measurements of H₂O and HDO lines, performed during northern spring in 1993 - 1995, indicate a water column density of 3 to

20 pr- μm (Clancy *et al.* 1996). Our measurements are consistent with these results; however they were performed about six months after aphelion, toward the end of northern summer so that a direct comparison is not possible.

In contrast, ground-based observations of the water vapor column density (Barker 1997; Sprague *et al.* 1997) and in-situ estimates of the H_2O abundance and vertical distribution (Smith *et al.* 1997; Titov *et al.* 1998) have been performed near the time of our observations. Mars Pathfinder landed on the Martian surface on July 4, 1997, and performed observations during 83 Martian days, i. e. until September 25, 1997. The Imager for Mars Pathfinder (IMP) took images of the Sun from the surface through the Martian atmosphere in narrow-band filters, some of them including the 0.94 μm H_2O band. Observations were carried out in the mornings and the evenings at low solar elevation angles, while the local time for the ISO observations was at the centre of the Martian disk 9:21 am. An average column density of (6 ± 4) pr- μm was derived, with an indication that water is confined to a layer 1-3 km thick near the surface. Mars Pathfinder landed in Ares Vallis, at a northern latitude of 20° . The IMP results can thus be compared with the ISO disk-integrated measurements for which the sub-Earth point had a latitude of $21\text{-}24^\circ$. It is interesting to try to compare the two datasets, in spite of their vastly different spatial resolution. This comparison indeed can make sense, because the ISO infrared measurements, although averaged over the Martian disk, are heavily weighted to the point of maximum surface temperature, which has the same latitude as the sub-solar point, and thus the same latitude as the Pathfinder site. Both ISO and Pathfinder datasets support the conclusion that water was confined in the lower atmosphere at low northern latitudes at the end of northern summer. Our higher value of the H_2O column density and saturation level is likely to be due to

the different local hour, as saturation is expected to be maximum at sunrise and sunset. But also spatial or temporal variations of the water abundance can contribute to the difference between IMP and ISO results. The ground-based measurements of Barker 1997, performed on July 5 and 6 and on August 18, were found to be consistent with the Pathfinder results, with an H_2O column density of about 13-15 pr- μm at early afternoon, in full agreement with the ISO results. We note, however, that the results of Sprague *et al.* 1997, obtained on July 12, tend to be higher (up to 32 pr- μm), which may imply some day-to-day variation of the water vapor abundance.

The emissivity of the Martian surface has been the main uncertainty in model calculations of the continuum flux from this primary calibration standard in the far infrared. Our measurement result of an emissivity for the disk average that falls from 0.97 to 0.92 between 50 and 180 μm lies between the lower value at radio wavelengths (Rudy *et al.* 1987) and the unit emissivity in the near infrared. It is hard to disentangle the relative contributions of atmospheric dust and surface to the disk emissivity. However, for opacity and surface temperature conditions representative of our observations, calculations based on the dust optical properties of Forget *et al.* 1999 suggest an apparent dust emissivity *increasing* from about 0.97 at 40 μm to 0.99 at 80 μm and essentially 1 at longest wavelengths. Therefore, the behaviour that we find, i.e. a *decreasing* disk emissivity longward of 50 μm , must be characteristic of the surface rather than of the atmospheric dust.

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The ISO LWS data presented in this paper were analyzed using the LWS Interactive Analysis Software, developed by RAL and IPAC (see Sidher *et al.* 1997).

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FIGURE CAPTIONS

1. Typical vertical temperature profile, derived from the Mars Climate Database (Forget *et al.* 1999) and adjusted to fit the 15 μm SWS spectrum.

2a. The observed/model ratio in the region of the H_2O lines at 5.6-7.3 μm . Top panel: Uniform models with H_2O mixing ratios (from top to bottom) of 4, 3, 2.5, 2 and 1.5×10^{-4} . Bottom panel: Saturated models with H_2O surface mixing ratios of 5, 4, 3, 2 and 1.2×10^{-4} (from top to bottom). Best fits are obtained when most of the residual absorptions/emissions, i.e. lines which are in the observation either stronger or weaker than in the model, are eliminated. This occurs for a constant $\text{H}_2\text{O} = 2.5 \times 10^{-4}$ or a saturated H_2O profile with 3×10^{-4} surface mixing ratio.

2b. The observed 5.6-8 μm spectrum of Mars (solid line), along with two fitting models. Short-dashed, thin line: H_2O mixing ratio = 2.5×10^{-4} , vertically uniform. Long-dashed, thick line: H_2O mixing ratio = 3×10^{-4} at surface and saturated above 13 km. The two models give essentially identical fits.

3. The ISO SWS grating spectrum compared to synthetic models with various emissivities in the 39-41 μm range. The measured spectrum has been normalized so that the flux level in the centre of the water lines agrees with the models. This allows a direct comparison of the line to continuum ratios between the observation and the models for different emissivities. From top to bottom in the continuum: $\epsilon = 1.0, 0.92, 0.75$. The water distribution is the same as in model 2a.

4. The SWS Fabry-Perot lines of H_2O compared to synthetic models. a: 39.38 μm ; b: 39.83 μm ; c: 40.34 μm ; d: 40.56 μm . Models: (1b) solid; (2b) dotted; (3) short-dash; (4) long-dash.

5. Comparison of the LWS grating spectrum in detector SW4 with models for different emissivities. The continuum has been normalized to 1. Black: measured spectrum, green: $\epsilon = 0.90$, red: $\epsilon = 0.95$, blue: $\epsilon = 1.00$

6. Emissivity as a function of wavelength derived from line-to-continuum ratios in an LWS end-to-end grating scan. The error bars were derived from the line fit; there is an additional, systematic uncertainty of ± 0.02 due to the error margins in the H_2O profile.

7. Comparison of an LWS Fabry-Perot spectrum around 62 μm with models for different emissivities. Solid line: measured spectrum, upper dotted line: $\epsilon = 1.00$, dashed line: $\epsilon = 0.95$, lower dotted line: $\epsilon = 0.90$.

TABLE I
Observations of Mars with ISO

Date	Time	AOT ^a	Wavelength (μm)	L_s ^b ($^\circ$)	$l_{(\text{SEP})}$ ^c ($^\circ$)
July 31	22:04-00:14	S06	2.3-45	157	126
August 5	21:33-22:13	S07	39.364-39.394	158	59
August 5	21:33-22:13	S07	39.823-39.850	158	59
July 29	22:29-23:22	S07	40.329-40.346	155	142
August 12	23:10-00:16	S07	40.554-40.572	162	18
August 15	21:11-23:36	L01	45-196	165	329
August 17	22:52-23:45	L03	61-63	166	323

^a Astronomical Observing Template

^b areocentric longitude of Mars

^c longitude of the sub-Earth point (westward increasing)

TABLE II

Atmospheric models of Mars

MODEL #	Q^a ($\times 10^{-4}$)	z^b (km)	$c(\text{water})^c$ (pr- μm)	ϵ^d
1a	2.5	Q const. with height	12.0	1.00
1b	2.5	Q const. with height	12.0	0.92
2a	3.0	13	12.0	1.00
2b	3.0	13	12.0	0.92
2c	3.0	13	12.0	0.75
3	4.0	15	15.5	0.92
4	2.0	11	8.5	0.92

^a H₂O mixing ratio^b saturation level^c column density^d emissivity