Simultaneous mapping of H$_2$O and H$_2$O$_2$ on Mars from infrared high-resolution imaging spectroscopy

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Abstract

New maps of martian water vapor and hydrogen peroxide have been obtained in November–December 2005, using the Texas Echelon Cross Echelle Spectrograph (TEXES) at the NASA Infra Red Telescope facility (IRTF) at Mauna Kea Observatory. The solar longitude $L_s$ was 332° (end of southern summer). Data have been obtained at 1235–1243 cm$^{-1}$, with a spectral resolution of 0.016 cm$^{-1}$ ($R = 8 \times 10^4$). The mean water vapor mixing ratio in the region [0°–55° S; 345°–45° W], at the evening limb, is 150 ± 50 ppm (corresponding to a column density of 8.3 ± 2.8 pr-µm). The mean water vapor abundance derived from our measurements is in global overall agreement with the TES and Mars Express results, as well as the GCM predictions, however its spatial distribution looks different from the GCM predictions, with evidence for an enhancement at low latitudes toward the evening side. The inferred mean H$_2$O$_2$ abundance is 15 ± 10 ppb, which is significantly lower than the June 2003 result [Encrenaz, T., Bézard, B., Greathouse, T.K., Richter, M.J., Lacy, J.H., Atreya, S.K., Wong, A.S., Lebonnois, S., Lefèvre, F., Forget, F., 2004. Icarus 170, 424–429] and lower than expected from the photochemical models, taking in account the change in season. Its spatial distribution shows some similarities with the map predicted by the GCM but the discrepancy in the H$_2$O$_2$ abundance remains to be understood and modeled.

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1. Introduction

High spatial and spectral resolution ground-based imaging spectroscopy of Mars in the infrared is a powerful tool for monitoring the narrow spectral signatures, due to the very low surface pressure, of atmospheric gases. This has been illustrated, in particular, by the maps of water vapor and hydrogen peroxide recorded with the Texas Echelon Cross Echelle Spectrograph (TEXES), mounted on the NASA Infra Red Telescope facility (IRTF) at Mauna Kea Observatory in June 2003 [Encrenaz et al., 2004, 2005]. These maps were obtained by comparing weak individual transitions of H$_2$O$_2$ and HDO, respectively, with a neighboring CO$_2$ weak line of comparable depth; mixing ratios were inferred from the direct ratio of the lines depths. At the time of these observations ($L_s = 206°$), both species were found in global agreement with the TES predictions and (in the case of H$_2$O) with the TES results. The first reported detection of H$_2$O$_2$ by Clancy et al. (2004), corresponding to $L_s = 251°$, was also in agreement with the models and with the TEXES map. However, a previous search for H$_2$O$_2$, performed with the same instrument in February 2001 ($L_s = 110°$) failed to detect this species and led to a stringent upper limit, hardly compatible with the photochemical models (Encrenaz et al., 2002). Recently, following an earlier suggestion by Atreya and Gu (1995), Atreya et al. (2006, 2007) have pointed out that ele-
trostatic discharges appear during dust storms and dust devils, when dusty grains are highly charged, and could lead to strong and localized sources of hydrogen peroxide. A spatial and seasonal monitoring of H$_2$O$_2$ thus appears important, in order to better understand its temporal variations.

On November 30–December 1, 2005, we have obtained a new map of H$_2$O$_2$, still using the TEXES instrument. We now have constraints on the H$_2$O$_2$ abundance and spatial distribution for several values of $L_s$, which allow us to test photochemical models under different seasonal conditions (Lefèvre et al., 2006). In addition, a new water vapor map, also obtained during our 2005 run using a HDO transition, can also be compared with global climate models and with space data, in particular from MAWD/Viking, TES/MGS and Mars Express.

In this paper, we present the new maps of H$_2$O and H$_2$O$_2$ obtained in 2005 with TEXES. Section 2 describes the observations, the modeling and the retrieval method. The H$_2$O$_2$ and H$_2$O maps are presented in Sections 3 and 4, respectively. In Section 5, we compare our results with LMD/GCM simulations coupled with a photochemical model.

2. Observations and modeling

2.1. Observations

Observations of Mars were performed on November 30–December 1, 2005, using the Texas Echelon Cross Echelle Spectrograph (TEXES; Lacy et al., 2002) at the NASA Infra Red Telescope facility (IRTF). This instrument covers the 5–25 µm range with a spectral resolving power of about 8 × 10$^4$ and a spatial sampling of 0.3683 arcsec (pixel size). Our spatial resolution, after binning, was about 1.5 arcsec. We have selected the 1235–1243 cm$^{-1}$ spectral interval (8.05–8.10 µm), partially used in our 2003 run, which contains transitions of H$_2$O$_2$ and HDO.

At the time of our observations, the diameter of Mars was 17 arcsec. The solar longitude was 332$^\circ$ (end of southern summer). The latitudes of the sub-solar point (SSP) and the sub-terrestrial point (STP, at the disk center) were 11$^\circ$ S and 19$^\circ$ S, respectively. The local time of the STP was 11:00 am. Due to the planet’s rotation, its western longitude ranged, between the beginning and the end of the observations, from 65$^\circ$ to 95$^\circ$ W on the first night and from 55$^\circ$ to 85$^\circ$ W on the second night. The western longitude of the SSP ranged from 45$^\circ$ to 75$^\circ$ W on the first night and from 35$^\circ$ to 65$^\circ$ W on the second night. The radial velocity was +9 km/s, corresponding to a Doppler shift of −0.038 cm$^{-1}$. As in the case of our 2003 observations, we used a 1.1 × 8 arcsec$^2$ slit and we mapped alternatively the northern and southern hemispheres of Mars (with regard to the celestial pole), by orienting the slit along the N–S celestial axis and by moving it from west to east by 0.5 arcsec steps. Each individual map was recorded in about 10 min. The northern and southern maps, measured in the continuum, were centered by superimposing the limbs of each individual map, both for the north and the south hemispheres. Then, the final maps were built using the difference in declination coordinates of the northern and southern components, and checking the adjustment of their limb position. The data reduction and radiance calibration are described in Encrenaz et al. (2002, 2004). Calibration of the TEXES spectra follows the radiometric method commonly used for millimeter and submillimeter observations (Rohlf and Wilson, 2004). Calibration frames consisting of 3 elements (black chopper blade, sky and low emissivity chopper blade) are systematically taken before each observing sequence, and the difference (black–sky) is taken as a flat field; a complete description of the procedure can be found in Lacy et al. (2002). As in the case of our 2003 run, the data were not corrected for telluric absorption in order to preserve the original S/N ratio.

In the 1235–1243 cm$^{-1}$ range, the strongest lines of the spectrum are absorption lines due to H$_2$O and CH$_4$ in the terrestrial atmosphere. In addition, the spectrum shows doppler-shifted martian lines due to CO$_2$ (in particular at rest frequencies of 1235.67 and 1241.58 cm$^{-1}$, see Fig. 1), HDO (at 1236.5 and 1239.95 cm$^{-1}$ rest frequencies) and H$_2$O$_2$ (at 1241.53 and 1241.61 cm$^{-1}$ rest frequencies, see Fig. 1). It should be noted that the CO$_2$ lines and the HDO line are not visible in the spectrum of the terrestrial atmosphere; the strongest terrestrial absorption lines are due to H$_2$O and CH$_4$. The H$_2$O$_2$ lines and the 1239.95 cm$^{-1}$ HDO transition, associated to the CO$_2$ 1241.55 cm$^{-1}$ transition, have been used to retrieve the H$_2$O$_2$ and HDO maps in our previous studies (Encrenaz et al., 2004, 2005).

Fig. 1 shows a part of the spectrum recorded on December 1, between 1241.45 and 1241.75 cm$^{-1}$, where the two strongest H$_2$O$_2$ lines are observed, in addition to martian CO$_2$ lines. This spectrum is averaged over a region centered around 55$^\circ$ S latitude and 0$^\circ$ W longitude, covering the [30$^\circ$, 80$^\circ$ S] latitude range and the [45$^\circ$, 315$^\circ$ W] longitude range. As shown in Fig. 2, this area, close to the southern evening limb of the planet, corresponds to a maximum depth of the martian CO$_2$ lines; this maximum is the combination of the high airmass and the relatively large temperature contrast between the surface and the atmosphere. The same area has been used for spectral summation on both nights, but the longitude of the corresponding area are shifted by 10$^\circ$ between the two nights.

Fig. 3 shows a map of the continuum radiance at 1241.4 cm$^{-1}$. The maximum radiance (33 erg/s/cm$^2$/sr/cm$^{-1}$) is located south of the SSP and corresponds, for a surface emissivity of 1.0, to a maximum brightness temperature of 275 K. It can be seen that the maximum radiance is about two times lower than the one measured in June 2003 (Encrenaz et al., 2005). This change is mostly due to the seasonal change (summer in 2003, nearly equinox in 2005): maximum brightness temperatures, extracted from the European Martian Climate Database (EMCD; Lewis et al., 1999; Forget et al., 2006) are 320 K and 285 K for the 2003 and 2005 runs, respectively.

Other continuum measurements, obtained during the first night of our run, lead to a similar map. In Section 5.1, we discuss this result in comparison with the predictions of the EMCD.
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Fig. 1. The raw TEXES spectrum at 1241.45–1241.75 cm$^{-1}$ (December 1, 2005). The two martian CO$_2$ lines (at 1241.54 and 1241.68 cm$^{-1}$) and the two H$_2$O$_2$ lines (at 1241.49 and 1241.57 cm$^{-1}$) are Doppler-shifted by $-0.038$ cm$^{-1}$.

Fig. 2. Map of the CO$_2$ line depth at 1241.58 cm$^{-1}$ (rest frequency). It can be seen that the area of maximum contrast is close to the southern evening limb of the planet. This area has been used for the spectral summation shown in Fig. 1. The longitude of the central meridian is $70^\circ\pm15^\circ$ W.

2.2. Retrieval of gas mixing ratio

We have modeled the martian lines using a line-by-line radiative transfer code (Encrenaz et al., 2004, 2005). Spectroscopic data were taken from the GEISA data bank (Jacquinet-Husson et al., 2005). In addition, the line positions and the intensities of the weak CO$_2$ isotopic lines, not listed in GEISA, were calculated using the work of Rothman (1986) and Toth (1985). In order to model the mean spectrum (Fig. 1), we used a surface temperature of 250 K (corresponding to the continuum radiance), an airmass of 2.5, and we extracted from the EMCD database the thermal profile corresponding to the area covered by our selection. We then adjusted the surface pressure in order to fit the depth of the weak CO$_2$ lines. The GCM thermal profile corresponds to $T(z = 0) = 215$ K, $T(z = 10 \text{ km}) = 190$ K and $T(z = 20 \text{ km}) = 175$ K. As the CO$_2$ line is weak (as well as the H$_2$O$_2$ and HDO lines), the temperature above 20 km has no effect on the line modeling. Best fits were obtained for surface pressures of 6 mbar on November 30 and 5 mbar on December 1.

In the case of the November 30 data, we selected a CO$_2$ transition (Fig. 4) at 1235.64 cm$^{-1}$ (Doppler-shifted position). It is a doublet of 2 superimposed transitions at 1235.675 cm$^{-1}$ and 1235.676 cm$^{-1}$ (rest frequencies), respectively, which have both an intensity of $0.903 \times 10^{-25}$ cm molecule$^{-1}$, and respective energy levels of 673.45 and 673.43 cm$^{-1}$. This CO$_2$ line was used for comparison with the HDO transition at 1236.295 cm$^{-1}$ (rest frequency) which has an intensity slightly larger than the one at 1240 cm$^{-1}$, used in Encrenaz et al. (2005). The fits are shown in Section 3 (1241 cm$^{-1}$, Fig. 5) and Section 4 (1236 cm$^{-1}$, Fig. 7b).

For retrieving mixing ratios out of our data, the ideal method would consist in retrieving the temperature profile in each point of the disk and using it for modeling the spectrum. This method, however, would require us to rely upon model results to estimate the surface and atmospheric temperatures. As in the case of our previous studies (Encrenaz et al., 2004, 2005), we have chosen another method by which we infer the mixing ratios from the line depth ratios of the absorption lines. Indeed, as discussed below, calculations show that when the lines are optically thin, the line depth mixing ratio has only a weak dependence upon the atmospheric and geometric parameters. Here the line depth is defined as the fractional absorption at the line center. This quantity is calculated from the ratio of the radiance
at the line center divided by the half-sum of the continuum on each side of the line.

The lines we have been using in our present and past studies have depths of a few percent and are optically thin, with the exception of the CO\textsubscript{2} line at 1241.6 cm\textsuperscript{-1} which has a depth of 7.5%. Taking into account the instrumental convolution, the optical depth at the line center is about 0.5. The departure from the optically thin regime is expected to induce an uncertainty which needs to be quantified. In order to validate our method, we have built a grid of spectra corresponding to a large range of parameters. We have modeled all the lines which have been used in the present study (CO\textsubscript{2} at 1235.6 and 1241.6 cm\textsuperscript{-1}, H\textsubscript{2}O\textsubscript{2} at 1241.53 and 1241.61 cm\textsuperscript{-1}, HDO at 2136.3 cm\textsuperscript{-1}). We have allowed for variations of the mixing ratio by a factor of 2, the airmass from 1.0 to 2.5, and the lower atmospheric temperature gradient by a factor of 2. The temperature contrast between the surface temperature and the $T(\zeta = 0)$ temperature was allowed to range from 0 to 30 K. Calculations show that, in all cases, for both H\textsubscript{2}O\textsubscript{2} and HDO transitions, for a given mixing ratio, the variation of the line depth ratio, computed with the different models, is always less than 30%; this uncertainty is indeed not negligible and must be kept in mind when interpreting the maps.

3. H\textsubscript{2}O\textsubscript{2} mapping

On December 1, we observed the H\textsubscript{2}O\textsubscript{2} doublet around 1241 cm\textsuperscript{-1}, previously used in Encrenaz et al. (2004) to retrieve the H\textsubscript{2}O\textsubscript{2} map. This doublet, at rest frequencies of 1241.53 and 1241.61 cm\textsuperscript{-1}, respectively, has the advantage of bracketing the weak CO\textsubscript{2} line at 1241.58 cm\textsuperscript{-1}, which can be used to retrieve the [H\textsubscript{2}O\textsubscript{2}]/[CO\textsubscript{2}] ratio. The spectrum, however, looks different from the one observed in June 2003 (Encrenaz et al., 2004) because the Doppler shift is negative, while it was positive in 2003. As a result, there is no more contamination by the strong telluric CH\textsubscript{4} absorption at 1241.8 cm\textsuperscript{-1} (Fig. 1, to be compared with Fig. 3 of Encrenaz et al., 2004).

Fig. 5 shows the TEXES spectrum in the same area as for Fig. 1, corrected for the continuum slope (by adjusting the continuum on each side of each line) and compared to synthetic models. It can be seen that the best fit is obtained for a H\textsubscript{2}O\textsubscript{2} mixing ratio of 15 ppb, a value significantly lower than the value retrieved in June 2003 in the region of maximum S/N (Encrenaz et al., 2004); this region was located in the vicinity of the sub-solar point, in the [10° N, 35° S] latitude range and the [100°–150° W] longitude range. Note, however, that in June 2003 (before opposition) this area corresponded to the morning side; in December 2005, after opposition, the maximum CO\textsubscript{2} line depth (and hence the maximum sensitivity) is observed in the evening side.

As shown in Fig. 5, there is a slight mismatch (by about 0.009 cm\textsuperscript{-1}) of the position of the 1241.62 cm\textsuperscript{-1} line, attributed to H\textsubscript{2}O\textsubscript{2}. This effect was already observed in our previous Encrenaz et al. (2004) analysis, and was also present on another doublet component at 1234.05 cm\textsuperscript{-1}. Because over half a dozen H\textsubscript{2}O\textsubscript{2} transitions were identified, we think that these small discrepancies do not question the H\textsubscript{2}O\textsubscript{2} identification. The offsets might be due either to instrumental effects or to uncertainties in the spectroscopic parameters of the ν\textsubscript{4}H\textsubscript{2}O\textsubscript{2} band.

Fig. 6 shows the retrieval of the H\textsubscript{2}O\textsubscript{2} map. The map of the H\textsubscript{2}O\textsubscript{2} mixing ratio (Fig. 6b) is inferred from the ratio of the mean depth of the two H\textsubscript{2}O\textsubscript{2} lines (Fig. 6a) by the CO\textsubscript{2} line depth (Fig. 2). In Section 5, we discuss the comparison of the H\textsubscript{2}O\textsubscript{2} map with the predictions generated by the photochemical model coupled with the LMD/GCM.

In order to validate our method further, we have selected two other points in the map for which we have extracted the EMCD thermal profile. The first one is the STP at the disk cen-
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Fig. 6. Retrieval of the H$_2$O$_2$ mixing ratio map (December 1 data): (a, left) map of the H$_2$ line depth (average of the 1241.53 and 1241.61 cm$^{-1}$ lines); (b, right) O$_2$ the H$_2$O$_2$/CO$_2$ line depth ratio [(b)/(a)]. As shown in Fig. 5, an H$_2$O$_2$ mixing ratio of 15 ppb corresponds to an H$_2$O$_2$/CO$_2$ line depth ratio of 0.13 (green area). The SSP is indicated with a white dot. The longitude at the central meridian is 70° (±15°) W. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

4. HDO mapping

As in the case of our earlier study (Encrenaz et al., 2005), the water vapor map was retrieved from the mapping of a HDO transition, assuming a constant D/H ratio over the martian disk. This assumption is discussed in more detail below. The HDO abundance was measured using two different transitions: (1) 1236.3 cm$^{-1}$ (November 30), and (2) 1240.0 cm$^{-1}$ (December 1). The 1240.0 cm$^{-1}$ transition was already used in the analysis of the 2003 data (Encrenaz et al., 2005). However, in the present case, the negative Doppler effect shifts the line in the close vicinity of a terrestrial H$_2$O absorption line centered at 1240 cm$^{-1}$. Thus, we have not considered this transition in our analysis.

The other HDO transition has a rest frequency of 1236.295 cm$^{-1}$ and is doppler-shifted to a frequency of 1236.26 cm$^{-1}$. Its intensity, at standard temperature and pressure conditions, is $3.84 \times 10^{-24}$ cmolec$^{-1}$, and its energy level is 469 cm$^{-1}$ which, under martian conditions, corresponds to an intensity about twice stronger the transition used in June 2003 ($I = 2.42 \times 10^{-24}$ cmolec$^{-1}$, $E = 577$ cm$^{-1}$). Fig. 7 shows (a) the raw spectra of the HDO transition (the CO$_2$ nearby transition used for comparison is shown in Fig. 4), in the selected area (same as in Fig. 1) as defined in Section 2.1, and (b) the fit of the HDO line, ratioed to the nearby continuum, compared with synthetic models. The atmospheric parameters (the same as described in Section 2.2) allow us to fit also the 1235-cm$^{-1}$ CO$_2$ line. It can be seen that the best fit is obtained for a H$_2$O mixing ratio of 150 ppm, which corresponds to a column density of 8.3 pr-µm.

As in Encrenaz et al. (2005), we assume a constant HDO/H$_2$O mixing ratio of 5 times the terrestrial value, as derived by Krassnopolsky et al. (1997). This assumption may be incorrect, as fractionation effects are expected to be associated to water condensation and sublimation, leading to a change in the D/H ratio. These effects have been studied by Mumma et al. (2003), Montmessin et al. (2005) and Novak et al. (2007). Montmessin et al. (2005) have calculated the expected D/H ratio as a function of latitude and seasonal cycle. Their analysis shows that for $L_s = 332°$, between 60° S and 30° N latitudes, the D/H ratio is between 4.8 and 5.0 times the terrestrial value. However, calculations show a significant gradient of the D/H ratio between mid-northern latitudes and the north pole, with values ranging from 5 times down to 2.5 times the terrestrial value. The error associated with our hypothesis is thus less than 4% for all lati-
Fig. 7. (a, left) The raw TEXES spectrum at 1236.26 cm$^{-1}$ (HDO line). (b, right) The TEXES HDO line at 1236.3 cm$^{-1}$, corrected for the Doppler shift and ratioed to the nearby continuum, compared with synthetic models. Model parameters are described in the text. Black: TEXES data. Models: HDO = 100 ppm (green), 150 ppm (red), 200 ppm (blue). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Fig. 8. Retrieval of the H$_2$O mixing ratio map (November 30 data): (a, left) map of the HDO line depth at 1236.3 cm$^{-1}$; (b, right) the HDO/CO$_2$ line depth ratio. An H$_2$O mixing ratio of 150 ppm corresponds to an HDO/CO$_2$ line depth ratio of 0.3 (green area). The SSP is indicated with a white dot. The longitude at the central meridian is $80^\circ \pm 15^\circ$ W. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

The H$_2$O mixing ratio map is retrieved using the same method as for H$_2$O$_2$, with the 1235-cm$^{-1}$ CO$_2$ line being used for comparison. Fig. 8 shows (a) the map of the HDO line depth and (b) the map of the HDO/CO$_2$ line depth ratio. The map of the 1235-cm$^{-1}$ CO$_2$ line depth shows a behavior similar to that of the 1241-cm$^{-1}$ CO$_2$ line (Fig. 2).

As in the case of the H$_2$O$_2$ map (Section 3), we have modeled the HDO and CO$_2$ spectra in the two other specific locations used for the November 30 data (the STP at [75° W, 20° S] and the second point at [15° W, 10° N]). As a result, the mixing ratios calculated from the model are lower than our inferred mixing ratios by 8% in the first case and 2% in the second case, respectively. These departures are well within the 30% accuracy mentioned above (Section 2.2).

5. Discussion

The season of our observations ($L_s = 332^\circ$) is known to be quite peculiar. For instance, during the previous martian
year (January 2004) the Thermal Emission Spectrometer (TES) detected a rise of dust opacity just before this period. At $L_s = 332^\circ$, this led to a relatively dusty atmosphere everywhere between the south pole and about $30^\circ$ N, with absorption dust optical depth at 1075 cm$^{-1}$ scaled at 610 Pa around 0.4 (corresponding to a visible dust optical depth around 1). Unfortunately, TES was no longer operational at the time of our observations. Dust observations performed with Themis aboard Mars Odyssey (M.D. Smith, personal communication) suggests that a similar event took place in November–December 2005, although it was not as strong as the year before. Nevertheless, the presence of airborne dust significantly warmed the atmosphere which must have been devoid of water ice clouds during daytime, as also suggested by the Themis data. In such conditions, water vapor was not trapped in the lower atmosphere because of condensation, and it is likely that H$_2$O as well as HDO was well mixed vertically. The water vapor column density is thus simply linked to the H$_2$O vertical mixing ratio.

5.1. Surface temperatures

The mapping of the surface temperature, from the continuum measurement, is very straightforward and the two maps obtained on November 30 and December 1 (Fig. 3) show a similar behavior. The maximum surface temperature (Fig. 9a) is observed at a latitude of about $40^\circ$ S and at about the same longitude as the SSP.

Fig. 9b shows the surface temperature as predicted by the LMD/GCM for $L_s = 330^\circ–335^\circ$. It can be seen that the location of the maximum observed temperature (30 degrees south of the SSP) is different from that predicted by the GCM. Similarly, comparison with the TES observations at 2 pm obtained at the same season the previous martian year (and with which the GCM differs by less than 10 K everywhere) suggest that the maximum surface temperature should be between $30^\circ$ and $0^\circ$ S rather than between $55^\circ$ and $25^\circ$ S.

We also note that the observed TEXES continuum brightness temperatures at 1241 cm$^{-1}$ are colder than the predicted surface temperature ($\sim 290$ K). This could be partly due to some uncertainty in the absolute calibration of the TEXES data. However, it is also likely that the brightness temperatures at 1241 cm$^{-1}$ does not correspond to the kinetic surface temperature because of (1) non-unit surface emissivity effect and (2) the absorption and emission of colder airborne dust particles. On the one hand, according to TES measurements, the surface emissivity at 1240 cm$^{-1}$, is close to 0.95 rather than 1.0 (Smith et al., 2000). Assuming a surface emissivity of 0.95, the inferred maximum temperature is about 277 K. One the other hand, as mentioned above, at the time of our observations, the martian atmosphere was probably relatively dusty, with vertical absorption dust optical depth at 1075 cm$^{-1}$ (measured by TES for the same $L_s$ over previous martian years) up to 0.4. The dust absorption is thought to be weaker at 1241 cm$^{-1}$ but it is not negligible. Assuming the dust optical single scattering properties from Forget (1998), one can estimate that the absorption dust optical depth $\tau$ at 1241 cm$^{-1}$ is about half the absorption at 1075 cm$^{-1}$, and that it could have reached 0.2. Assuming a surface temperature of 280 K and a mean airborne dust temperature of 220 K, one can estimate the order of magnitude of the apparent cooling effect of dust on brightness temperature at 1241 cm$^{-1}$ (scattering is neglected): $-3.5$ K for $\tau = 0.1$, $-7$ K for $\tau = 0.2$, $-10$ K for $\tau = 0.3$, $-13$ K for $\tau = 0.4$, $-16$ K for $\tau = 0.5$. Values above $\tau = 0.2$ are shown to illustrate the cooling of dust for oblique viewing angle and/or in low topography regions (higher
Fig. 10. The H$_2$O$_2$ mixing ratio as predicted by the GCM for conditions close to our observations. The longitude at the central meridian is 60° W. The local hour at the central meridian is 12:00.

Fig. 11. The distribution of the water vapor mixing ratio, as predicted by the GCM for conditions close to our observations. The longitude at the central meridian is 60° W. The local hour at the central meridian is 12:00.

The H$_2$O$_2$ mixing ratio observed in December 2005 ($L_s = 330^\circ$–335°) is significantly lower than the one inferred in July 2003 ($L_s = 206^\circ$), and its spatial distribution is very different. The maximum value is about 15 ppb while it was 40 ppb in 2003; its distribution is more or less spread over the disk in 2005, with a clear minimum along a meridional stripe in the southern hemisphere, while it peaked in a single location, close to morning limb and equator, in 2003. The low value recorded in 2005 was also confirmed by Clancy (2006, private communication) who inferred an upper limit of 15 ppb from disk-integrated submillimeter observations in November 2005.

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The H$_2$O$_2$ map as expected from a photochemical coupled with the LMD/GCM for the conditions of our observations ($L_s = 330^\circ$–335°). The photochemical calculations (Lefèvre et al., 2004) have been adjusted (taking into account the GCM parameters) in order to optimize the agreement on the water vapor abundance between the GCM and the TES and PFS/Mars Express data along the whole seasonal cycle (Fouchet et al., 2007). The maximum value of H$_2$O$_2$ predicted by the GCM is about 30 ppb around [120° W, 40° S], while our maximum, not far from this area ([90° W, 50° S] on the TEXES map), is only 16 ppb.

While our 2003 observations were in a good agreement with the GCM predictions, we are now, as in 2001, in a situation where the observed H$_2$O$_2$ abundance is lower than the predictions. We note that our 3 data sets correspond to 3 different seasons: the H$_2$O$_2$ upper limit obtained in February 2001 was derived at the time of northern solstice ($L_s = 110^\circ$), while those of June 2003 corresponded to southern solstice ($L_s = 206^\circ$) and the present ones are close to equinox ($L_s = 332^\circ$). Regarding the spatial distribution of the H$_2$O$_2$ abundance, we note that the model does exhibit a meridional stripe of lower intensity, as observed in our data. However the contrast between this minimum and its surroundings is about 25% at most in the model, while it exceeds 50% in our observations. More theoretical work will be needed to resolve the discrepancies between the models and the observations.

5.3. H$_2$O maps

Fig. 11 shows the expected distribution of the water vapor mixing ratio, as predicted by the GCM (Forget et al., 1999; Montmessin et al., 2004) under the conditions of our observations ($L_s = 330^\circ$–335°). The GCM water cycle model used is similar to the one described in Montmessin et al. (2004), although in the simulations used here, the northern water ice polar cap albedo and the clouds microphysics were slightly modified.
in order to match (within a few pr-micrometers) the recently revised value of TES water retrieval (M.D. Smith, personal communication) which are now in better agreement with Mars Express observations (e.g., Fouchet et al., 2007). The mean overall mixing ratio shown in Fig. 11 (about 160 ppm) is consistent with our result.

However the spatial distribution of water vapor shows some differences. The GCM map shows a enhancement in the southern hemisphere, with a local maximum around 30° W. In contrast, we observe a maximum H₂O mixing ratio on the evening side around 0°–20° S latitude. Spatial variations, presently not predicted by the models and possibly associated with the local hour, appear to be present in the observed water vapor spatial distribution, and need to be understood and modeled.

Our results can be compared with previous space measurements of the martian water vapor, either from Viking, TES/MGS or Mars Express. The comparison, however, is limited by the fact that space data do not provide instantaneous maps over the martian disk, but measurements along a given meridian at constant local hour. In our model, an H₂O mixing ratio of about 100 ppb (corresponding to 5.5 pr-µm; Melchiorri et al., 2007; Fouchet et al., 2007). This is consistent with the minimum value of the TEXES map observed in the central part of the southern martian disk. We note, however, that the locations of the observations are different, as the longitude range of Olympus Mons (around 130° W) was not in the TEXES field of view in 2005.

5.4. Conclusions

The TEXES observations have allowed us to obtain quasi-simultaneous maps of the surface temperature, H₂O₂ and H₂O. The main conclusions of this study can be summarized as follows:

- Surface temperature maps are consistent during the two nights. The maximum surface temperature, derived from the 1241.4 cm⁻¹ continuum, is 277 K, taking into account an emissivity of 0.95 at 1240 cm⁻¹, which is lower that the GCM predictions. In addition, the location of this maximum is at a higher southern latitude than expected from the model; this effect remains to be understood and modeled;
- The H₂O₂ abundance is found to be lower than the GCM prediction (as in February 2001), but its spatial distribution shows some similarities with the models; in particular, there is evidence for a clear meridional stripe of minimum abundance, which also appears, with less contrast, in the GCM map;
- The water vapor map shows, as the one of hydrogen peroxide, longitudinal variations, with a maximum toward the evening side, which was not predicted by the GCM. The mean water vapor mixing ratio, however, is broadly consistent with GCM predictions and with previous measurements. A precise comparison with previous data sets is however very difficult, because the space data were acquired for a given longitude and at a given local time.

In summary, ground-based infrared mapping of Mars, at high spatial and spectral resolution, is a valuable tool, fully complementary with the space orbiter data. Indeed, these maps provide us with instantaneous and simultaneous maps of H₂O₂ and H₂O, which cannot be obtained from spacecraft, and are important for studying possible diurnal effects and constraining global circulation models.

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