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Global structure and composition of the martian atmosphere with SPICAM on Mars express

Jean-Loup Bertaux [a,*], O. Korablev [b], D. Fonteyn [c], S. Guibert [a], E. Chassefière [a], F. Lefèvre [a], E. Dimarellis [a], J.P. Dubois [a], A. Hauchecorne [a], M. Cabane [a], P. Rannou [a], A.C. Levasseur-Regourd [a], G. Cernogora [a], E. Quémerais [a], C. Hermans [c], G. Kockarts [c], C. Lippens [c], M. De Maziere [c], D. Moreau [c], C. Muller [c], E. Neefs [c], P.C. Simon [c], F. Forget [d], F. Hourdin [d], O. Talagrand [d], V.I. Moroz [b], A. Rodin [b], B. Sandel [e], A. Stern [f]

[a] *Service d'Aéronomie du CNRS/IPSL, BP. 3, 91371 Verrières-le-Buisson, France*
[b] *Space Research Institute (IKI), 84/32 Profsoyuznaya, 117810 Moscow, Russia*
[c] *Belgian Institute for Space Aeronomy, 3 av. Circulaire, B-1180 Brussels, Belgium*
[d] *Laboratoire de Météorologie Dynamique/IPSL, University Paris 6, 4 Place Jussieu, BP 102 Paris, France*
[e] *Lunar and Planetary Laboratory, 1040 E, 4th Street, University of Arizona, Tucson, AZ 85721, USA*
[f] *SouthWest Research Institute, Boulder, CO 80302 Colorado, USA*

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Abstract

SPectroscopy for the Investigation of the Characteristics of the Atmosphere of Mars (SPICAM) Light, a light-weight (4.7 kg) UV–IR instrument to be flown on Mars Express orbiter, is dedicated to the study of the atmosphere and ionosphere of Mars. A UV spectrometer (118–320 nm, resolution 0.8 nm) is dedicated to nadir viewing, limb viewing and vertical profiling by stellar and solar occultation (3.8 kg). It addresses key issues about ozone, its coupling with H_2O, aerosols, atmospheric vertical temperature structure and ionospheric studies. UV observations of the upper atmosphere will allow studies of the ionosphere through the emissions of CO, CO^+, and CO_2^+, and its direct interaction with the solar wind. An IR spectrometer (1.0–1.7 μm, resolution 0.5–1.2 nm) is dedicated primarily to nadir measurements of H_2O abundances simultaneously with ozone measured in the UV, and to vertical profiling during solar occultation of H_2O, CO_2, and aerosols. The SPICAM Light near-IR sensor employs a pioneering technology acousto-optical tunable filter (AOTF), leading to a compact and light design. Overall, SPICAM Light is an ideal candidate for future orbiter studies of Mars, after Mars Express, in order to study the interannual variability of martian atmospheric processes. The potential contribution to a Mars International Reference Atmosphere is clear.

Keywords: Martian atmosphere; Global structure and composition; SPICAM; Mars express

1. Introduction

SPectroscopy for the Investigation of the Characteristics of the Atmosphere of Mars (SPICAM) Light, a 4.7 kg UV–IR spectrometer to be flown on Mars Express orbiter (ESA MEX mission), is dedicated to recover most of the science that was lost with the demise of Mars 96, where the SPICAM set of sensors was focused on atmospheric studies. The new configuration of SPICAM Light includes an optical sensor (3.8 kg) and an electronics block (0.9 kg). This total mass

* Corresponding author. Tel.: +33-1-6920-2999; fax: +33-1-6647-4245.
E-mail address: bertaux@aerov.jussieu.fr (J.-L. Bertaux).

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of 4.7 kg may be compared to the 46 kg of the SPICAM instrument that was implemented on Mars 96. The visible part (300–700 nm), and the IR part above 1.7 μm do not exist in this "Light" version of SPICAM. The optical sensor consists of two channels. A UV spectrometer (118–320 nm, resolution 0.8 nm) is dedicated to nadir viewing, limb viewing and vertical profiling by stellar and solar occultation. An IR spectrometer (1.0–1.7 μm, resolution 0.5–1.2 nm or $\lambda/\delta\lambda = 1300$) is dedicated primarily to nadir measurements of H_2O abundances, and vertical profiling during solar occultation of H_2O and aerosols, and 1.27 μm $O_2(^1\Delta_g)$ emission of ozone (Korablev et al., 2002). A simple data processing unit (DPU, 0.9 kg) provides the interface of these channels with the spacecraft. The optical scheme of both channels is indicated on Fig. 1.

In nadir orientation, SPICAM UV is essentially an ozone detector, measuring the strongest O_3 absorption band at 250 nm in the spectrum of the solar light scattered back from the ground (Fig. 3). In the stellar occultation mode the UV Sensor will measure the vertical profiles of CO_2, temperature, O_3O_2 clouds and aerosols (Fig. 7). The density/temperature profiles obtained with SPICAM Light will constrain and aid in the development of the meteorological and dynamical atmospheric models, from the surface to 160 km in the atmosphere. This is essential for future missions that will rely on aerocapture and aerobraking. UV observations of the upper atmosphere will allow studies of the ionosphere through the emissions of CO, CO^+, and CO_2^+, and its direct interaction with the solar wind. Also, it will allow a better understanding of escape mechanisms and estimates of their magnitude, crucial for insight into the long-term evolution of the atmosphere. The SPICAM Light near-IR sensor employs a pioneering technology acousto-optical tunable filter (AOTF), and it is dedicated to the measurement of water vapour column abundance in the IR simultaneously with ozone measured in the UV, in the Nadir orientation. In solar occultation mode this channel permits to study the vertical structure of H_2O, CO_2, and aerosols.

The instrument is built in cooperation between Service d'Aéronomie/IPSL in France, BISA in Belgium, and IKI in Moscow. Co-investigators are the authors of Bertaux et al. (2000).

2. Nadir mode viewing

In this mode, used mostly around pericenter, SPICAM is oriented towards the nadir, like the other optical instruments (PFS, OMEGA, HRSC camera), and UV and IR spectra of the backscattered solar light are recorded along the track at a rate of one per second. Figs. 2–5 give an idea of the shape of the albedo spectra that will be recorded by SPICAM. Actually, the level of the albedo is of course below 1, and its value is dependent on the quantity of aerosols and their optical properties in the atmosphere of Mars. The AOTF system is such that a certain number of wavelength micro windows may be selected and scanned, according to a care-

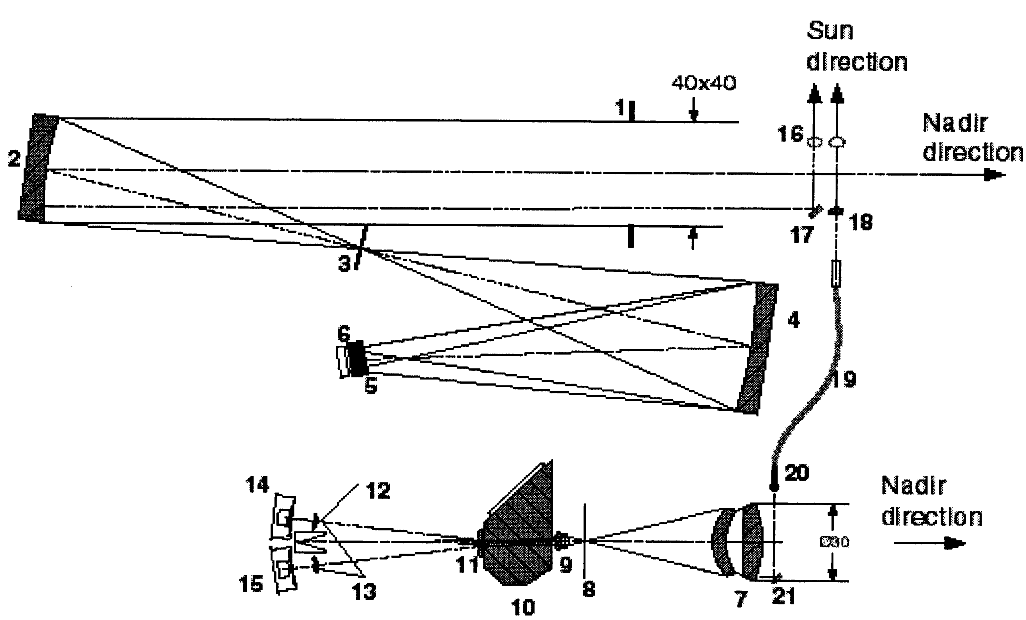

Fig. 1. Optical scheme of the UV and IR channels of SPICAM Light: (1) aperture blend of the UV channel; (2) off-axis parabolic mirror; (3) slit (can be changed from wide to narrow, by a mechanical actuator); (4) concave UV grating; (5) intensifier; (6) CCD; (7) IR channel objective; (8) IR FOV diaphragm; (9, 11) collimating lenses; (10) AOTF crystal; (12) light trap for undiffracted light; (13) detector proximity lenses; (14) "extraordinary" beam detector; (15) "ordinary" beam detector; (16) solar opening (closed by shutter when not looking to the Sun); (17, 21) flat mirror; (18) IR solar entry; (19) optical fiber; (20) fiber collimator.

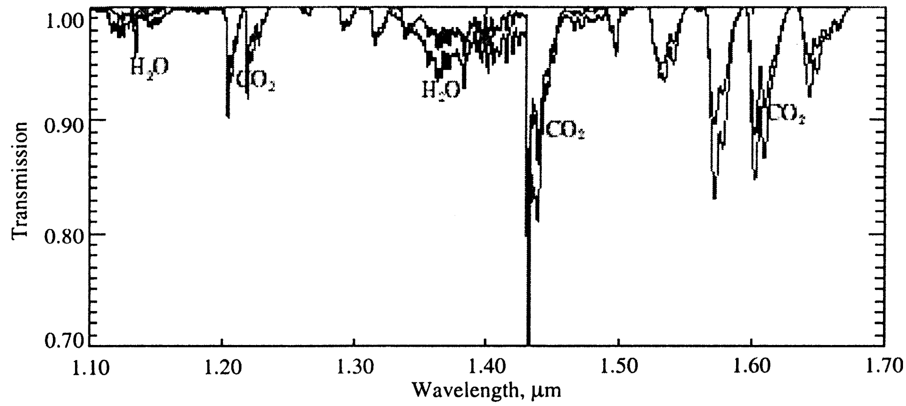

Fig. 2. Line-by-line spectra of atmospheric transmission in Nadir. Spectra are computed for a water vapour abundance of 15 and 50 pr µm (offset in H_2O bands) and for surface pressures of 6 and 7 mbar (offset in CO_2 bands). This wavelength domain is the very one used by MAWD experiment on board Viking orbiters.

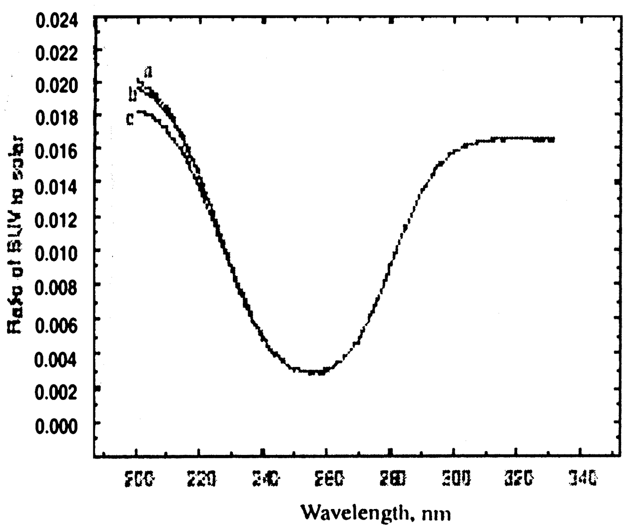

Fig. 3. Modtran computations for Nadir geometry. Solar zenith angle 60°, ozone total abundance 20 µm-atm. A possible effect of H_2O_2 is considered: no H_2O_2 (curve a); H_2O_2 column of 2×10^{16} cm^{-2} (curve b) and 2×10^{17} cm^{-2} (curve c).

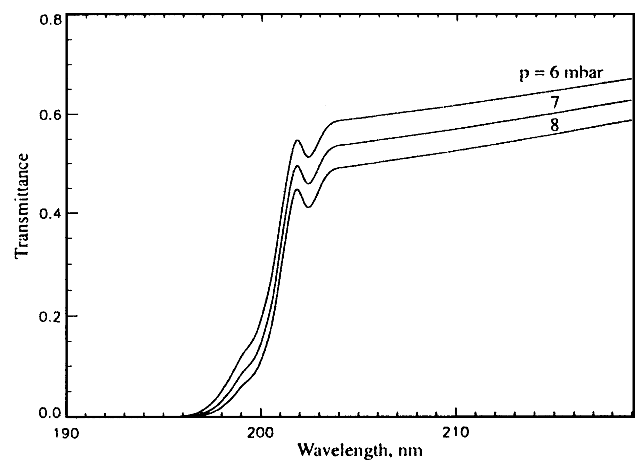

Fig. 4. Modification in UV transmission spectrum in Nadir configuration with surface pressure. There is the possibility to determine the surface pressure, from the wavelength cutoff around 200 nm of the UV albedo of Mars atmosphere + ground.

ful selection of various modes (for instance, around the water vapour band). New modes may also be introduced by telecommand.

3. Occultation measurements

The instrument may also work in the solar or stellar occultation mode. In this mode, the whole Mars Express spacecraft is oriented and maintained with the SPICAM FOV pointing (open loop) to a star or to the sun. Then, the orbital drift makes the line of sight penetrating more and more deeply in the atmosphere of Mars, down to total occultation. The stellar occultation technique offers three decisive features:

- an absolute concentration derived from a relative measurement (no need of instrument calibration, self calibrated method),
- excellent vertical resolution, whatever is the distance to the planet (because the star is a point source),
- the accuracy of altitude knowledge, at variance with limb emission methods, is independent of the attitude of the spacecraft. The LOS is entirely determined by the direction of the star in the sky (known) and the position of the S/C on its orbit (see Fig. 7).

Stellar occultations will be done preferably on the night side of the orbit, and will not affect the operation of dayside mapping instruments. SPICAM will measure the vertical distribution of CO_2, temperature, O_3, aerosols, O_2 and possibly H_2O_2 by using the technique of stellar occultation. Solar occultations are also possible

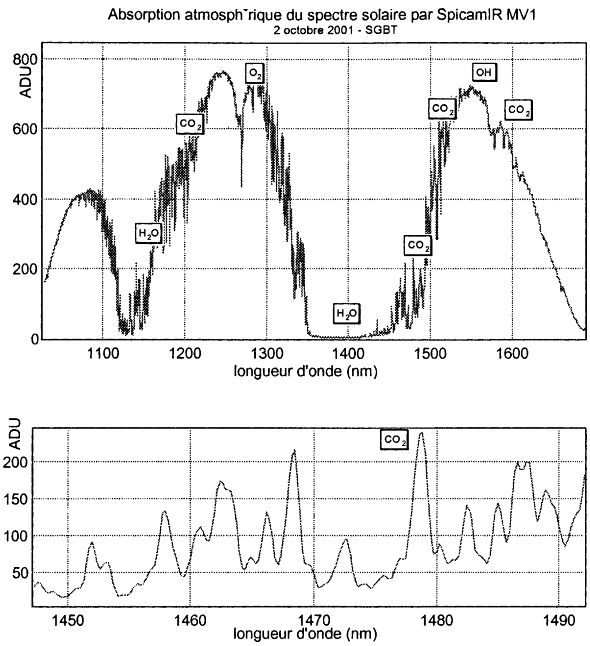

Fig. 5. Spectrum of solar light scattered by the parking lot of Service d' Aéronomie as measured by the AOTF channel (ADU engineering units). All recognized Earth atmospheric absorptions are indicated. The details of the lower panel indicates what is the actual spectral resolution.

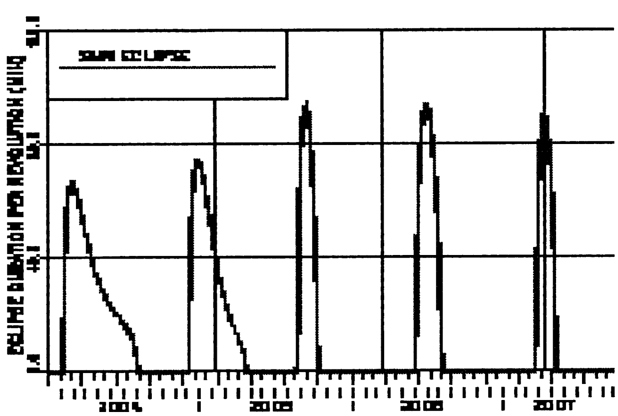

Fig. 6. Periods of solar eclipse at orbit G3A. (Figure adopted from Hechler and Yanes, 1999.)

at various periods of the mission (Fig. 6). Several or at least one occultation per orbit (3 per day) are foreseen, the limiting factor being the spacecraft orientation as a resource to be shared between the various experiments. For solar occultation, the IR channel is also activated to retrieve H_2O vertical profile with a high accuracy. A lateral viewport of SPICAM is used in this mode, in order to avoid solar light entering the FOV of the other optical instruments.

Because the CO_2 cross-section presents an enormous dynamic range in the UV, the CO_2 absorption may be detected already at an altitude of 150 km. For decreasing tangential heights, the CO_2 manifests itself (Fig. 7)

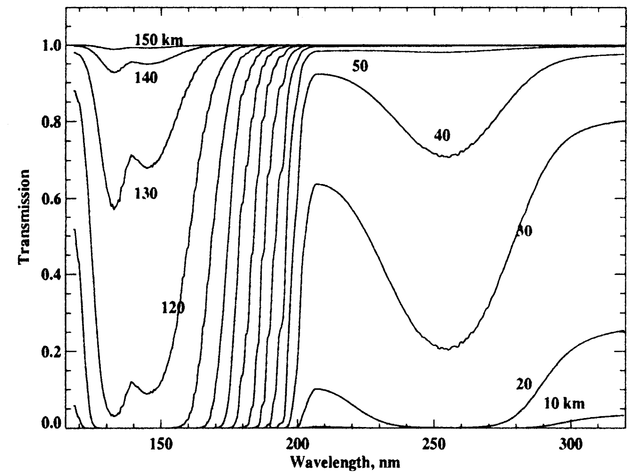

Fig. 7. Simulated transmission spectra in stellar occultation geometry for tangential altitudes from 150 to 10 km with the step of 10 km. Ozone absorption is seen at 250 nm, while CO_2 absorption is seen in the range 120–200 nm.

by a sharp cut-off which increases in wavelength, up to 200 nm at $z = 10$ km. Longward of 200 nm, the transmission spectrum is dominated by dust and CO_2 Rayleigh extinction, with the additional trough at 255 nm due to ozone. The depth of this trough is a direct measure of ozone line density. From the given S/N in stellar occultation mode, the O_3 line density N_h accuracy will depend on the UV magnitude of the star. From extensive simulations (Korablev et al., 2001) it can be estimated that the accuracy on the O_3 line density will be about 2% for about 20 stars in the sky and the measuring threshold corresponding to an absorption of 1%, corresponds to $N_h = 10^{15}$ mol cm^{-2} (horizontal) and local density of 3.5×10^7 cm^{-3} at all altitudes $z > 15$ km (Fig. 8). The temperature dependence of ozone cross-section will be dealt with thanks to an iterative method

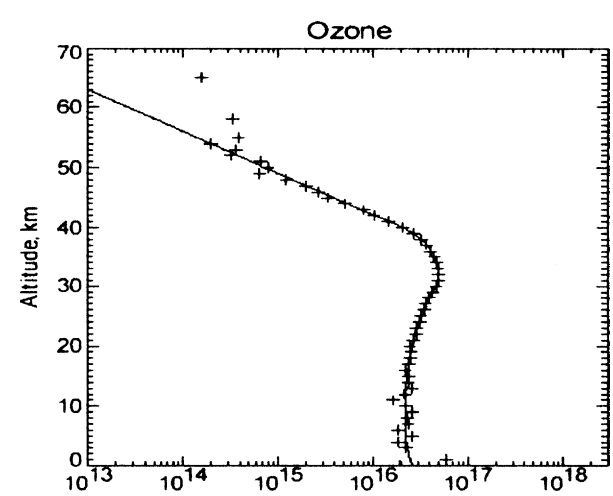

Fig. 8. Simulated retrieval of ozone from the transmission. Solid line is the model and crosses are the retrieved line densities of ozone.

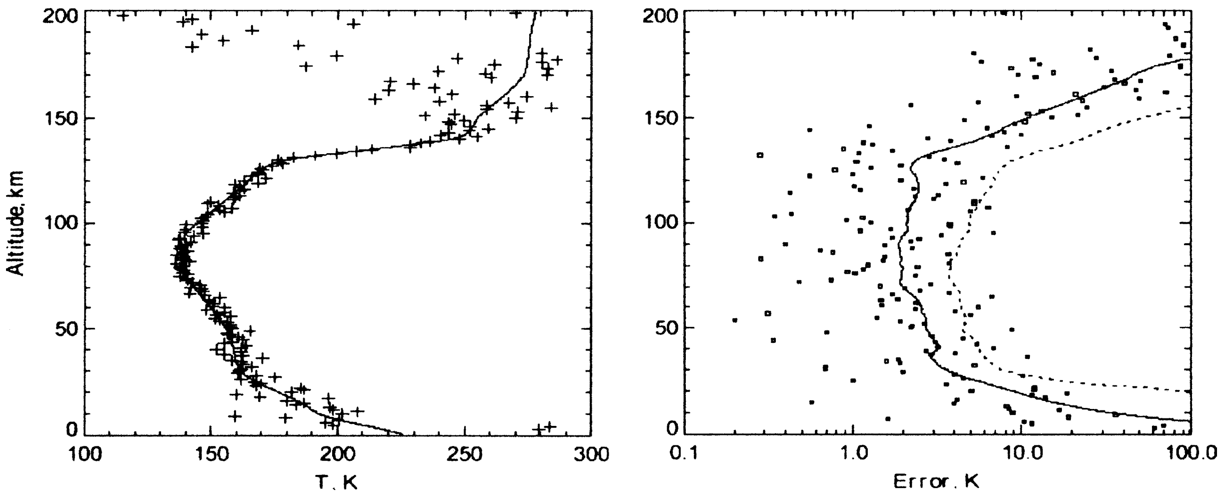

Fig. 9. Left: simulated retrieval of temperature from the transmission of Fig. 7 and retrieval of CO_2 (not shown). Solid line is the forward temperature model, and crosses are the retrieved temperatures. On the right is plotted the difference between forward and retrieved temperature, which indicates the accuracy of the method.

of the spectral/vertical inversion, assuming hydrostatic equilibrium. The Rayleigh extinction above 200 nm can be computed from the CO_2 line density determined below 200 nm, and the remaining continuous absorption above 200 nm may be attributed to dust/aerosol for a determination of its vertical distribution and spectral characteristics in the UV.

3.1. CO_2 density and temperature profile

Once the line density of CO_2 is determined from the transmission spectra, the local density $n(z)$ is determined from an Abel inversion. Then, the hydrostatic equation allows temperature to be determined. As for O_3, the accuracy on the CO_2 line density will be about 2% for 20 stars. The accuracy of retrieved temperature is estimated to be ±3 K in the whole range of altitude, starting at 130–160 km at top level, while the lowest altitude achieved will depend on the absorption by aerosols or clouds, and most likely located between 5 and 20 km (Fig. 9). In addition, these simulations have shown that O_2 may be retrieved, with the current estimate of 0.1% mixing ratio. This would be the first time that O_2 is systematically measured in the atmosphere of Mars.

4. Airglow observations at the limb

4.1. Study of the ionosphere from UV

Most of the ionosphere lies below the nominal pericenter altitude of Mars Express (300 km) and unfortunately in situ measurements will impossible. However, the natural UV airglow of the atmosphere offers a possibility to study by remote sensing the ionosphere and its temporal behaviour as a function of solar-wind parameters. Fig. 10 shows the spectrum of dayglow recorded by Mariner 6 and 7 UV spectrometer (Barth

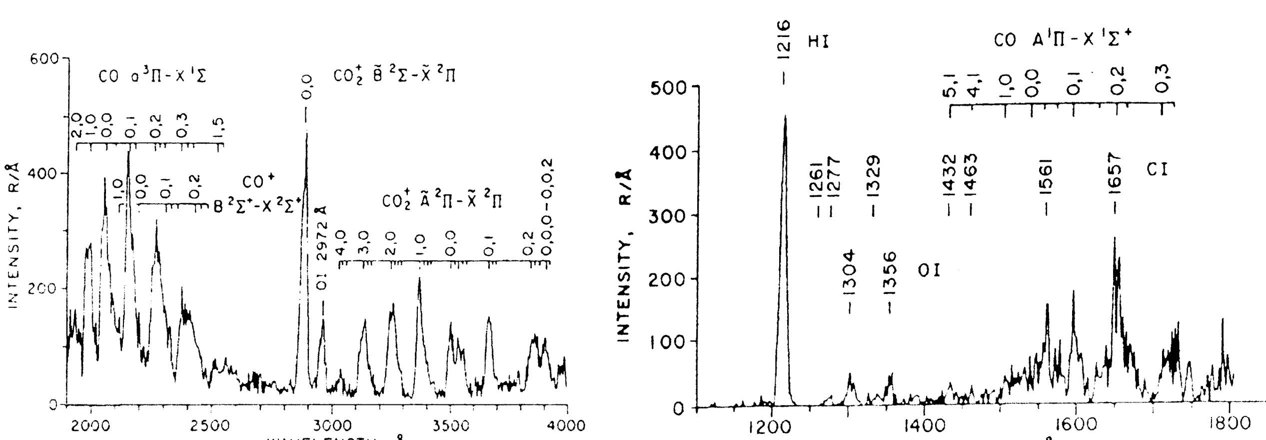

Fig. 10. Mariner 6 and 7 ultraviolet spectrum of the upper atmosphere of Mars at a resolution of 20 Å. Spectrum at the limb at an altitude between 140 and 180 km, and includes four individual observations (Figure adopted from Barth et al., 1971).

et al., 1971). The main ionisable neutral constituent is CO_2, and the CO_2^+, transition ($B^2\Sigma_u + -X^2\Pi_g$) at 289 nm (or 2890 Å) is produced by photoionisation of CO_2 from solar UV at $\lambda < 69$ nm. The other band CO_2^+ ($A^2\Sigma_u$–$X^2\Pi_g$) between 300 and 400 nm is produced by a combination of photoionisation and fluorescence scattering on CO_2^+ ions. The SPICAM UV long wavelength cut-off is at 320 nm, which is enough to measure the (4,0) and 3,0) transitions of the A–X band, partly produced by fluorescence of CO_2^+. Clearly, SPICAM ionospheric measurements are somewhat indirect, but when combined with SPICAM neutral CO_2 measurements, electron measurements obtained by radio occultation, ASPERA particle measurements, Marsis radar sounding and sophisticated ionosphere models, they will certainly provide useful measurements to constrain the ionosphere of Mars. The UV detector, a proximity focus combination of an image intensifier and a CCD, provides up to 60 ADU spread over 8 pixels for each photon detected by the photocathode, ensuring its detection and a good photometric sensitivity (see Fig. 9).

4.2. O_2 airglow on the limb in the IR

Recently, a dayglow at 1.27 μm $O_2(^1\Delta_g)$ emission was observed, and mapping of this emission is reported by Krasnopolsky and Bjoracker (2000). The predicted signal-to-noise ratio for SPICAM will be superior to 20 in a single spectral bin, or 200–300 for the entire band. This emission results from the photo-dissociation of O_3 molecule by one solar UV photon, and is therefore a sensitive way to measure ozone, quite different than the UV one. It will be particularly interesting to compare the two methods. Since this emission is quenched by CO_2 at low altitudes, it is sensitive only to ozone above 10–20 km. Therefore, if this emission may be distinguished in the spectrum observed in the nadir viewing mode as a spike over the continuum, then the combination of UV and IR in the nadir mode will be able to discriminate the ozone at high altitude from the total ozone. Combined with the H_2O measurements, it will yield an important corpus of data to study the aeronomic coupling of water vapor and ozone in the atmosphere of Mars. According to the spectrum of Krasnopolsky and Bjoracker (2000), and taking into account the coarser spectral resolution of SPICAM (1300 instead of 40,000), we estimate that the intensity peak would be of about 1–3% over the adjacent continuum.

5. Conclusion

The measurements of SPICAM will take their full power when compared and analyzed in the context of various models, for the benefit of these models: a photo-chemistry model (in development by Franck Lefèvre at Service d' Aéronomie), a GCM model of the atmosphere, extended to the thermosphere, and a model of the ionosphere. The results will provide an important input for the Mars International Reference Atmosphere.

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