THE MARTIAN OZONE LAYER AS SEEN BY SPICAM/MARS-EXPRESS. F. Lefèvre[1], J.-L. Bertaux[1], S. Perrier[1], S. Lebonnois[2], O. Korablev[3], A. Fedorova[3], F. Montmessin[1], and F. Forget[2]. [1]Service d'Aéronomie, Institut Pierre-Simon Laplace, France (UPMC, box 102, 75252 Paris cedex 05, franck.lefevre@aero.jussieu.fr), [2]Laboratoire de Météorologie Dynamique, France (UPMC, box 99, 75252 Paris cedex 05), [3]Space Research Institute, Russia (IKI, 84/32 Profsovuznava, 117810 Moscow, Russia).

Introduction: Ozone is one of the most important, and one of the most reactive species in the Martian atmosphere. It controls the UV flux that reaches the ground, thus the habitability of the planet. The abundance of ozone on Mars is directly controlled by the local concentration of HO_x radicals (H, OH, and HO_2). HO_x are also responsible for the apparent stability of the Mars atmosphere, by recycling the CO_2 molecules photodissociated in the upper atmosphere. HO_x have never been directly observed, but ozone can be used as an efficient tracer of these species. Thus, the distribution and variability of ozone is related to fundamental problems in the Martian atmosphere. The comparison between ozone measurements and model predictions can highly improve our understanding of the whole photochemistry and stability of the Martian atmosphere.

We will present in this paper an overview of the ozone measurements performed from the SPICAM instrument on board Mars-Express. These are the first continuous observations of ozone on Mars since the Mariner missions in the early 1970s [1,2]. The wealth of data obtained by SPICAM has considerably broadened the pool of available O_3 data with which to validate the photochemical models. We will use a General Circulation Model (GCM) with chemistry to analyze them and to evaluate our progress towards a quantitative understanding of the Martian photochemistry.

SPICAM Instrument Overview: SPICAM is a 4.7 kg UV-IR dual spectrometer which has been operational on board the European Mars-Express mission since January 2004 [3]. The orbiter has an elliptical polar orbit with a period of about 7 hours, a pericenter altitude of ~300 km and apocenter altitude of ~10000 km. SPICAM is mainly dedicated to the determination of atmospheric characteristics of Mars from the ground up to 160 km altitude, and ozone mapping is one of its major objectives. The spectral range of the UV imaging spectrometer (118-320 nm, resolution ~1.5 nm, intensified CCD detector) allows to cover the strong UV absorption of CO_2 ($\lambda < 200$ nm) and the Hartley ozone absorption band between 220 and 280 nm. For the purpose of ozone measurements, the Mars-Express spacecraft can be oriented in two different observation modes:

Nadir viewing. In nadir mode, SPICAM observes Mars through its atmosphere with a line of sight perpendicular to the ground. For each orbit, spectra are averaged over 50 seconds and divided by a data reference spectrum taken over Olympus Mons. A full radiative transfer forward model is then used in an iterative loop to fit the data with four parameters: the surface albedo at 210 nm and 300 nm, the dust opacity, and the daytime vertical ozone column, with a typical uncertainty of 10-15% [4].

Stellar occultations. In stellar occultation mode, the SPICAM UV field of view is pointed toward a star, and its detector records the stellar spectrum as the spacecraft drifts on its orbit and the star rises or sets behind the atmosphere of Mars. A reference spectrum of the star is measured outside the atmosphere, than all spectra during the occultation are ratioed to this reference stellar spectrum, to get atmospheric transmission spectra as a function of altitude. The O_3 slant column is then retrieved from the transmission obtained in the Hartley band. Finally, the nighttime vertical profile of ozone is inverted with an 'onion peeling' procedure and a vertical resolution of about 5 km [5].

Ozone Observations: Figure 1 displays the seasonal evolution of the O_3 vertical column measured by SPICAM (nadir mode) during the first Martian year of observation (MY27). This is the first O_3 mapping ever obtained on Mars, although the coverage in season and latitude is not as complete as desirable. In particular, few data are available at high latitudes. This is due both to the large solar zenith angles, and to the need to share observing time with other instruments. Moreover, there is a lack of data between $L_s = 70°$ and $L_s = 90°$, related to the period of solar eclipses that decrease power resources. However, the coverage of the SPICAM O_3 measurements is sufficient to describe the distribution and seasonal evolution of the Martian ozone layer with unprecedented detail. The ozone column is found to be highly variable with season, geography, and meteorology. It varies from essentially 0 to a maximum of about 30 μm-atm. The Martian ozone layer is very thin by Earth standards, corresponding to a maximum of 3 Dobson (one Dobson unit = 10 μm-atm), to be compared to a usual Earth's value of 300 Dobson units. As a result, the actinic flux reaching the ground of Mars in the UV is extremely high. At high latitudes of both hemispheres, the ozone column is maximum in winter, when condensation on polar caps suppresses most of the atmospheric water vapor. The largest ozone columns are found in the northern polar vortex (O_3 > 30 µm-atm) , in agreement with the early measurements of Mariner 9 [2]. Polar ozone is minimum in summer, indicating an efficient O_3 destruction by the HO_x radicals released from the large amounts of water vapor and sunlight. At low latitudes, SPICAM observations show an increase in O_3 in the aphelion season, with columns of the order of 2-3 µm-atm, to be compared to the amounts smaller than 1 µm-atm retrieved during the rest of the year. This result is in good qualitative agreement with previous O_3 measurements performed from Earth [6] or the HST [7,8].

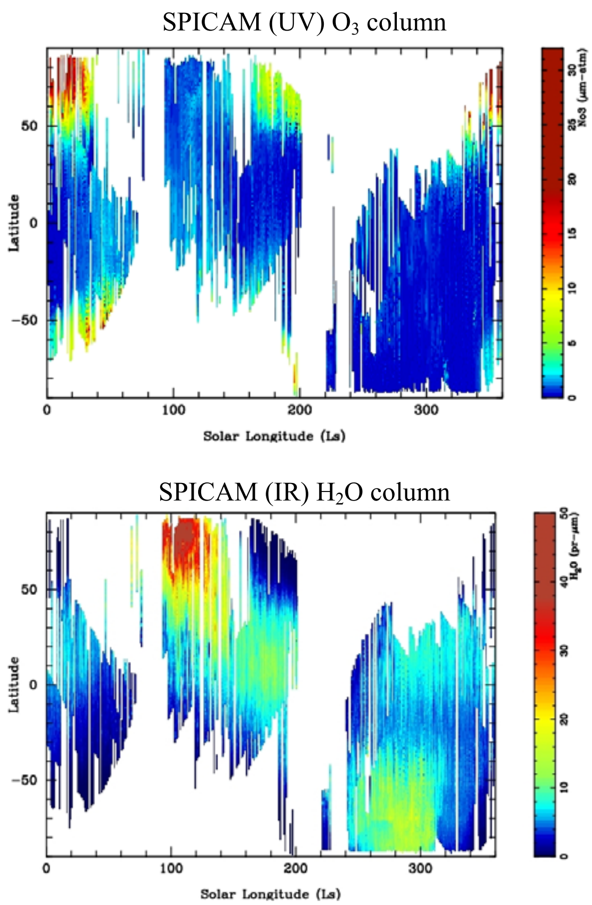

Figure 1. Top: Seasonal evolution of the zonally-averaged ozone vertical column (µm-atm) measured by SPICAM UV. Bottom: zonally-averaged water vapor column (precipitable-µm) measured by the infrared channel of SPICAM, not detailed here [9].

Because water vapor is the source of HO_x, which effectively control the local amount of ozone, water vapor and ozone are expected to be anticorrelated in the Martian atmosphere. The observation of O_3 and H_2O by SPICAM, both retrieved simultaneously in the UV and IR channels respectively, brings a clear evidence of this anticorrelation in Figure 1. Other aspects of the SPICAM O_3 measurements are the large orbit to orbit variability observed in winter at high latitudes, which is associated to the irregular shape of the ozone-rich polar vortex, and the systematic accumulation of O_3 in regions of low surface elevation, such as Hellas or Argyre. These phenomenons agree with 3D model predictions [10].

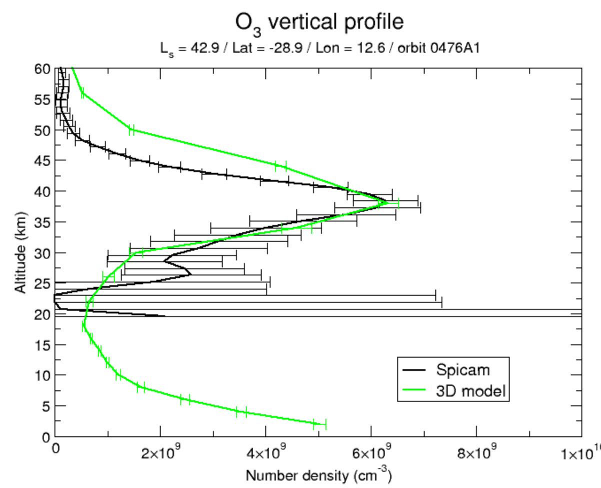

Figure 2. Example of O_3 nighttime vertical profile measured by star occultation with SPICAM (black curve) [5]. Coincident profile extracted from a 3D chemical simulation is also shown (green curve). L_s = 42.9°, 28.9S, 12.6E.

Before Mars-Express, only one single ozone vertical profile could be obtained by the Phobos 2 mission [11]. The quality was not excellent, partly because the quantity of ozone was small at the season and at the local time sampled by the instrument. With the numerous star occultations obtained by SPICAM, more than 400 vertical profiles have been obtained and analyzed as a function of latitude and season [5]. The results clearly show the presence of a nighttime O_3 layer located in the altitude range 30 to 60 km, only observed in the aphelion season (Figure 2). In addition, the top of a lower, near-surface O_3 layer is sometimes identified below 30 km when the dust opacity is low enough to track the star down to low altitudes. The upper O_3 layer is first seen at Ls = 11° at low northern latitude. Then, the ozone abundance at the peak (45 km altitude) tends to increase until L_s ~40°, when its stabilizes around 6-8 x 10^9 cm^{-3}. After L_s ~100°, the peak abundance starts decreasing again, and this ozone layer is no longer detected after L_s ~130°. This finding confirms the effectiveness of a mechanism first hypothesized by Clancy and Nair [12]: over the period L_s=180-

330° centered on perihelion, water vapor saturation occurs at high altitude (>40 km at L_s=250°), leading to considerable HO_x production and O_3 loss in the middle atmosphere. As a result, O_3 is essentially confined in the 'surface layer' below 20 km. During the rest of the year (L_s=330-180°), the altitude of water vapor saturation is lower (~10 km at L_s=90°) which reduces the HO_x production and allows the formation of an additional O_3 layer between 30-60 km altitude. The vertical distribution of ozone is therefore almost entirely driven to orbital (L_s) variations in the H_2O vertical distribution.

Comparison to Model Simulations: The measurements performed by SPICAM have been interpreted using our three-dimensional model of the Martian photochemistry described in Lefèvre et al. [10]. Our chemical model is an adaptation of the chemical package used in the Reprobus model developed earlier for the terrestrial stratosphere [13]. It provides a comprehensive description of the oxygen, hydrogen, and CO chemistries on Mars, and is implemented as a chemical subroutine into the GCM developed since the early 1990s at Laboratoire de Météorologie Dynamique (LMD), in collaboration with the University of Oxford (AOPP) and the Instituto de Astrofísica de Andalucía (IAA) [14].

For each photolyzed species we employ the most recent absorption cross-sections commonly used in the modeling of the Earth atmospheric chemistry. Photolysis rates are calculated off-line and are stored in a 4-dimensional lookup table as a function of the overhead CO_2 column, the overhead O_3 column, the solar zenith angle, and the temperature. For ozone studies the chemical model computes the three-dimensional distribution of 12 constituents ($O(^1D)$, O, O_2, O_3, H, OH, HO_2, H_2, H_2O, H_2O, CO, and CO_2) using 42 photolytic or chemical reactions. Most of the rates and branching ratios that we have adopted are those recommended by the Jet Propulsion Laboratory 2006 compilation [15]. At each model timestep, the CO_2, H_2O, and other chemical fields are exchanged between the GCM and the chemical routine to achieve a fully interactive coupling between dynamics, radiation, water cycle, and chemistry. The coupled model is run on 32 vertical levels with a horizontal resolution of 64 longitudes by 48 latitudes (5.625°x3.75°).

O3 integrated column. Figure 3 shows the daytime O_3 column seasonal evolution calculated by the 3D model. It can be seen that the GCM reproduces well, in a zonally averaged sense, the main features of the O_3 distribution observed by SPICAM: winter pole maxima, summer minima, as well as the dichotomy aphelion/perihelion at low latitudes.

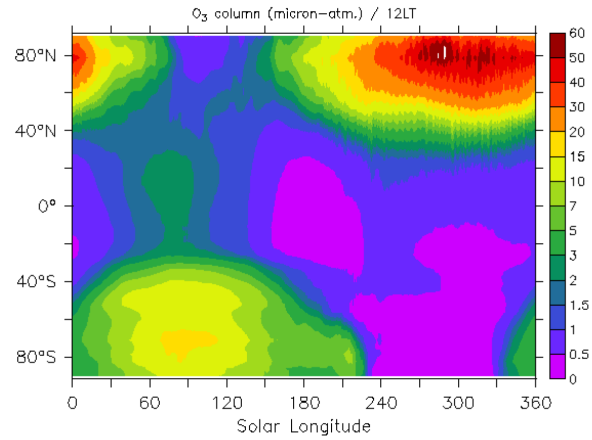

Figure 3. Seasonal evolution of the zonally-averaged daytime ozone vertical column (µm-atm) calculated by the 3D model.

Using strict citeria of spatial and temporal coincidence. SPICAM measurements have been then systematically compared to the GCM results in both modes of observation. Figure 4 shows the results of this point-by-point comparison in the 40-60N and 00-20N latitude bands. Our 3D simulation suggest that the O_3 amounts in the polar regions are well understood throughout the year. In winter, the quantities of ozone calculated by the model agree with the observations (including those of the pre-Mars Express era, not shown here), and reproduce well the considerable day-to-day variability that is associated to dynamical disturbances of the polar vortex. In summer, the lower than 1 µm-atm O_3 columns calculated at high-latitudes are also quantitatively consistent with all observational data. A new finding is that a good quantitative agreement between the model and SPICAM can also be achieved at low latitudes. This is a significant improvement over our previous studies [4, 9], which pointed to the too low ozone quantities produced by the model during the aphelion season. This difference is explained by the lower H_2O amounts now calculated by the model, which has been tuned to agree better with recently revised or newly available H_2O satellite data. As a result, our new simulation not only does reproduce the global increase in O_3 that is measured from perihelion to aphelion, but the amplitude of this orbital variation now agrees with SPICAM. However, two important points must be noted. First, we find that taking into account heterogeneous chemical reactions on ice clouds does improve the agreement between the model and SPICAM at all latitudes. This suggests that these processes play an important role in the Mars atmosphere, which needs to be investigated further. Second, it appears that the low-latitude O_3 columns retrieved from SPICAM tend to be smaller than those previously observed from Earth, in particular during the aphelion season. This discrepancy remains to be explained. We note however that playing with current uncertainties in absorption cross-sections or kinetics data does not allow the model to produce low-latitude O_3 colums much larger than those presented here.

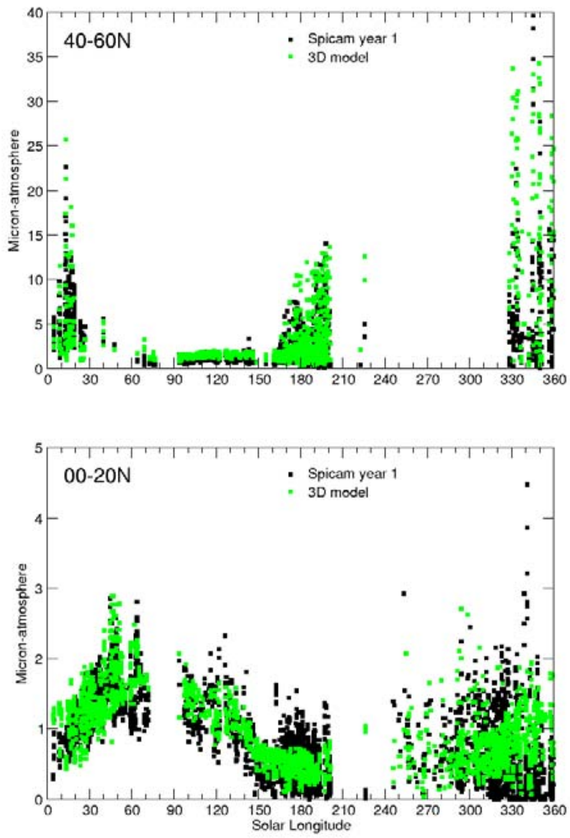

Figure 4. Comparison between O_3 columns measured by SPICAM (black) and coincident calculations by the 3D model (green). Match criteria are $\Delta t = \pm 1h$, $\Delta lat = \pm 1.9°$, $\Delta lon = \pm 2.8°$. Top: 40-60N latitude band. Bottom: 00-20N latitude band. Note the change in vertical scale.

O3 vertical profile. The seasonal/orbital evolution of the nighttime O_3 vertical profile calculated by the GCM is globally consistent with the SPICAM observations: the 'surface' O_3 layer is predicted throughout the year below 20-30 km altitude, which coincides rather well with the SPICAM measurements available in this altitude range; above 30 km, ozone is highly variable with latitude and season: our 3D model predicts O_3 abundances close to zero during the perihelion season, in good agreement with SPICAM, whereas maximum abundances are calculated near aphelion. The quantitative agreement between Spicam and the model is satisfactory over the L_s=40°-70° period (see Figure 2), when ozone reaches maximum abundances. However, the period during which measurable significant amounts of ozone are calculated above 30 km is too long in the model. In particular, the sharp drop-off in the O_3 amount observed by Spicam shortly after aphelion is not predicted to occur before L_s=150° in the GCM. This difference provides an interesting constraint on the seasonal evolution of the H_2O vertical distribution, which will be the subject of a forthcoming study.

References:

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