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OBSERVATIONS OF ATOMIC DEUTERIUM IN THE MESOSPHERE FROM ATLAS 1 WITH ALAE INSTRUMENT

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Abstract. During the first *ATLAS* mission, the ALAE Lyman α spectrophotometer collected various measurements of hydrogen and deuterium atoms, from the mesosphere, the thermosphere, the exosphere and the interplanetary medium. In this paper is presented a preliminary analysis of some observations of atomic deuterium, which Lyman α emission is excited by resonance scattering of solar photons. Nadir measurements along the sunlit Earth part of the orbit show that the emission changes as a function of solar zenith angle. Comparison with a simple model shows that,from the shuttle altitude of 300 km and at low solar zenith angles, the line-of-sight probes atomic deuterium down to 80 km of altitude (where O_2 absorption is complete), whereas at angles from 60° to 90°, the mesospheric part of the emission progressively vanishes. Then, the remaining emission mainly consist of the thermospheric part ($z \geq 100$ km). This type of observations provides a sounding of atomic deuterium at its peak production and concentration, and D atoms can be used as a proxy to H atoms (which cannot be observed from a satellite) in this particularly active region of the mesosphere.

1. Introduction

The ALAE (Atmospheric Lyman Alpha Emissions) instrument has successfully flown on board the *ATLAS* 1 shuttle mission, from March 24 to April 2, 1992. This Lyman α spectrophotometer, proposed and built in a cooperation program between Service d'Aéronomie du CNRS and the Institut d'Aéronomie Spatiale de Belgique, is devoted to the study of the various Lyman α emission processes from atoms of hydrogen and deuterium.

During the 9 days of the *ATLAS* 1 mission, the instrument was operated 84 times during a total of 103 hours, collecting more than twice the amount of data which was originally planned. With various modes of operation of the instrument, and various attitudes of the Atlantis shuttle, observations of H and D Lyman α emissions were obtained from the mesosphere, the thermosphere, the exosphere, some faint aurorae and the interplanetary medium, when looking to the nadir, the limb or the zenith.

During the first flight of ALAE on the *Spacelab* 1 mission in 1983, the Lyman α emission of deuterium atoms was detected for the first time when looking at the limb, by taking advantage of the long slant path above 110 km of altitude (Bertaux et al. 1984). However, the smaller emission coming from the nadir could not be identified in the signal. This time, thanks to a much higher sensitivity of the refurbished Flight Unit #2, placed on board *ATLAS* 1, the nadir emission of D atoms coming from the mesosphere and lower thermosphere could be easily detected. In this paper, we wish to present a sample of such observations and discuss the significance of this new type of observation, which allows to probe D atoms in an important chemical region (85 km of altitude) where H atoms cannot be observed directly from a satellite.

2. Model of nadir deuterium Lyman α emission

Figure 1 illustrates a model of vertical distributions of atomic hydrogen and deuterium in the atmosphere. The D profile was obtained by scaling the H concentration at the peak by a factor $1.6\ 10^{-4}$, which is the D/H ratio in the sea water. The two profiles were then computed taking into account the height of the turbopause, the thermal escape flux at the exobase, and the mass ratio of 2 for D and H atoms.

In the mesosphere, and in particular in the region of H production from H_2O photodissociation (80-90 km), the D profile may be considered as parallel to the H profile, in a first approximation.

On the dayside, D and H atoms are excited by the resonance scattering of the intense solar Lyman α line, at two distinct wavelength : 121.566 nm for H, and 121.533 nm for D. There are two resulting Lyman α emissions $I_{\rm H}$ and $I_{\rm D}$, well separated spectrally, since the thermal width of each of them is of the order of 0.003 nm. The ratio of intensities $I_{\rm D}/I_{\rm H}$ is larger than the D/H ratio, because deuterium is optically thin, whereas the medium is optically thick for H, and the H Lyman α emission is saturated when looking downwards from the Atlantis altitude of 300 km. In fact, it can be computed that for H, the Lyman α emission generated at 85 km cannot reach the altitude

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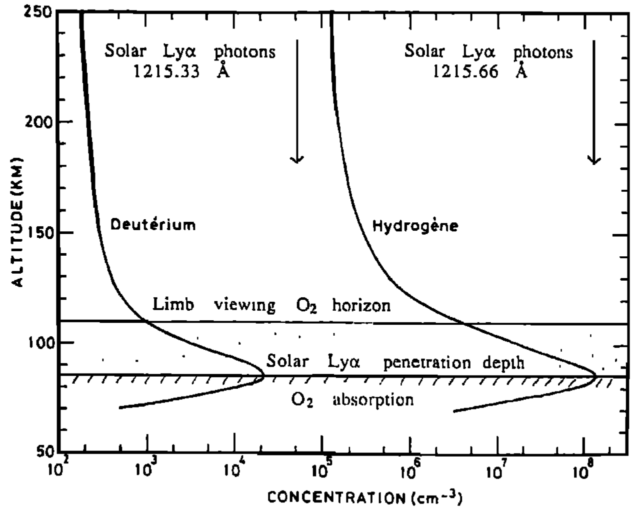

Fig. 1. Model of vertical distributions of D and H in the atmosphere between 50 and 250 km of altitude. The D distribution has been used to compute I_D, taking absorption of O_2 into account.

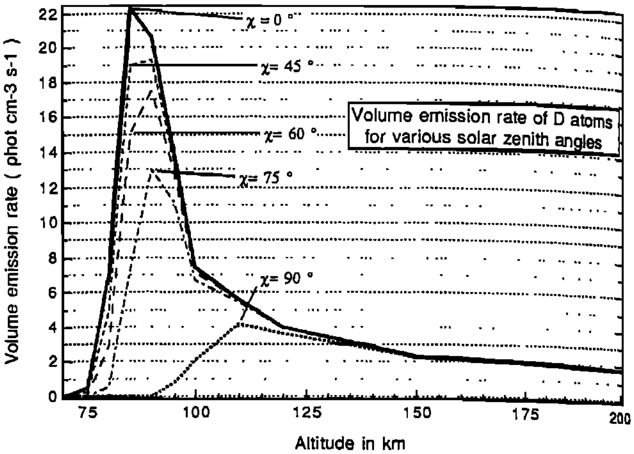

Fig. 2. Model of the volume emission rate of D atoms as a function of the altitude computed for various solar zenith angles. The dependence on the solar zenith angle is due to O_2 absorption. Above 110 km, where there is no O_2 absorption, ε_D is independent on χ.

of 300 km, making impossible the measurement of H at its peak production by remote sensing from a satellite. To our knowledge, there was only one direct measurement of H with a night-time rocket experiment (Sharp and Kita 1987).

Lyman α radiation from the Sun or re-emitted by H or D atoms is absorbed by O_2 in the atmosphere. With a cross section of 1.69 10^{-20} cm^{-2} for O_2 absorption at 121.533 nm, the vertical optical depth τ for O_2 absorption is 0.84 (for a US standard atmosphere model) at 80 km of altitude, just below the peak concentration of H. This is no fortuitous coincidence, since solar Lyman α radiation is the main source of H_2O photodissociation. Clearly, the penetration depth of solar Lyman α depends on the solar zenith angle χ. In figure 2 is displayed the volume emission rate $\epsilon_D(z)$ of D atoms as a function of altitude z and for various values of angle χ, computed from the D profile of figure 1 and a US standard atmospheric model for O_2

$$\epsilon_D(z) = \left(\frac{\pi e^2}{m_e c} f\right) F_s(\nu_D)\ [D](z)\ e^{-\left(\frac{\tau(z)}{\cos(\chi)}\right)} \qquad (1)$$

where $F_s(\lambda_D) = F_s(\nu_D)\frac{d\nu}{d\lambda} = 2.75\ 10^{11}$ phot cm^{-2} s^{-1} Å^{-1} is the exciting solar flux at the resonance wavelength of D atoms.

Figure 2 illustrates that, from a spacecraft looking at the nadir, the depth at which the D atoms are observed depends on the solar zenith angle χ. As the solar zenith angle increases, the mesospheric contribution progressively vanishes. Therefore, measurements performed for various values of χ will provide a sounding of D atoms between $\approx$ 80 km ($\chi = 0$) and $\approx$ 110 km of altitude ($\chi = 90°$). The model predicts a variation of I_D from 72 Rayleigh at $\chi = 0°$ to 41 R at $\chi = 90°$, for an observing altitude of 300 km, showing that 40 % of the emission I_D comes from a part of the mesosphere between 80 and 110 km.

In summary, measuring the nadir Lyman α emission of deuterium atoms offers a new possibility to sound the chemically very active region where H_2O (and HDO) is photodissociated, the D atoms serving as the most appropriate proxy to the H atoms which cannot be observed themselves directly.

Several factors will have to be taken into account when assessing the uncertainty on the determination of D absolute density. The photometric sensitivity of ALAE will be derived from observations according to the method applied for *Spacelab* 1 observations (Bertaux et al. 1989)which implies a comparison of data to geocoronal H models.

The solar fluxes $F_s(\lambda_D)$ and $F_s(\lambda_H)$ were measured several times in the past. Lemaire et al. (1978) used with *OSO* 8 spacecraft a high resolution solar profile averaged over many points of the solar disk, yielding $F_s(\lambda_D) = 2.75$ 10^{11} phot (cm^2 s Å)$^{-1}$ and $F_s(\lambda_H) = 3.3\ 10^{11}$ phot (cm^2 s Å)$^{-1}$. Both values were measured to vary with solar activity (Vidal-Madjar 1975). The final estimate of D concentration in the mesosphere will eventually be measured with an estimated uncertainty of $\pm$ 25 %. At present, our estimate may be wrong by up to a factor of 2.

The D/H ratio in the mesosphere is unknown at present. The sea value at 1.6 10^{-4} was taken in the present model for illustrative purposes. Paradoxically, ALAE is able to measure the deuterium concentration, but not the D/H ratio in the mesosphere.

The diurnal variation of D atoms was ignored in the present crude modeling. As a first cut, this is justified because more sophisticated photochemical models show a day to night variation of H atoms (and presumably D atoms) mainly below 80 km (Morcels et al. 1977), from where the D Lyman α emission is not visible from higher altitude. However, a more refined analysis, well beyond the scope of this paper, will take into account such a diurnal variation, together with the O_2 diurnal variations, equally ignored here, and transport, such as discussed by Liu and Donahue (1974) and Hunten and Strobel (1974).

3. Nadir observations of deuterium from *ATLAS* 1

The optical diagram of ALAE is shown in figure 3. The

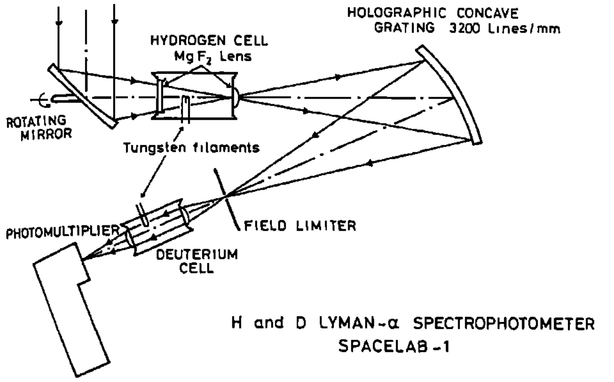

Fig. 3. Optical diagram of ALAE. H_2 and D_2 absorption cells may be activated separately or simultaneously.

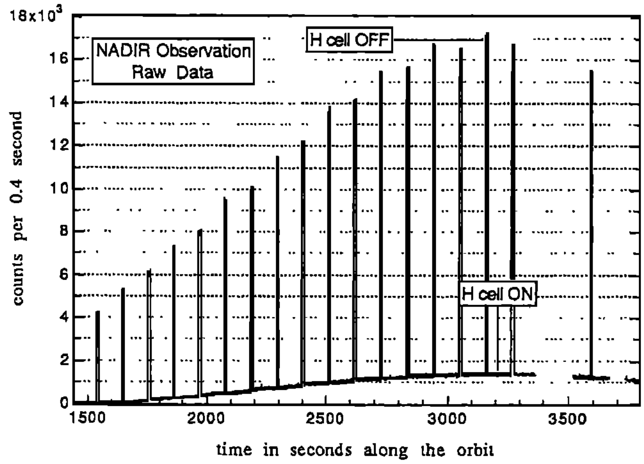

Fig. 4. Nadir raw data for counter C_1 as a function of time (the time scale is the same for figures 4, 5 and 6). These data were obtained with the large field of view (circular 2.5°). The peaks correspond to periods when the H_2 cell is off and measure the total emission. When the H_2 cell is on, roughly 90 % of the total emission is absorbed.

rotating mirror allows to look in a plane perpendicular to the long axis of the shuttle, and was kept fixed toward nadir during the observations presented below, Atlantis presenting its cargo bay to the Earth. The field-of-view is 2.5° diameter, circular, and the holographic grating isolates a bandwidth of about 4.5 nm centered at Lyman α, therefore excluding the strong OI line at 130.4 nm but including of course both I_H and I_D Lyman α emissions and also some NI 120 nm emission. One H_2 and one D_2 absorption cell are placed along the light path. Each cell can be activated independently, when a tungsten filament is electrically heated, dissociating molecules into atoms which scatter away from the main light path the photons at the line center. Photons are counted in two counters, sequentially opened in phase with a 5 Hz modulation of the D_2 cell : one counter C_1, is devoted to photons when the D_2 cell is off, the other counter C_2 being devoted to photons when the D_2 cell is activated. Each second, counts are accumulated in counters C_1 and C_2 for a total counting time of 0.4 second each. The difference $C_1 - C_2$ measures the absorption of light by the D_2 cell, therefore is directly linked to the I_D emission intensity. Usually the D_2 cell is used when the H_2 cell is already on.

In figure 4 is represented the counting rate of C_1 counter (D_2 cell off) during a particular orbit for constant nadir observations, from slightly before the morning terminator to somewhat after the local noon. The H_2 cell was activated most of time, and turned off for a short while at regular intervals to measure the total Lyman α emission plus NI 120 nm contribution (strong peaks regularly spaced). The intensity varies because the solar zenith angle varies along the orbit. The maximum counting rate is 17×10^3 counts per 0.4 second, corresponding roughly to an intensity of 30 kR (model prediction).The H_2 cell, when activated, absorbs more than 90% of the total emission (Lyman α and NI).

The remaining signal is also strongly variable with χ, the peak intensity being $\approx$ 2.5 kR. It includes the full contribution of NI 120 nm, not affected by the absorption cell, at a level of 1.5 kR (Meier 1991) and some H Lyman α not absorbed by the cell. A similar variation is obtained for counter C_2, not shown here for clarity. The difference $C_1 - C_2$ is entirely due to the partial absorption of the D Lyman α emission by the D_2 cell when the H_2 cell is activated. The data are shown in figure 5, after averaging over 60

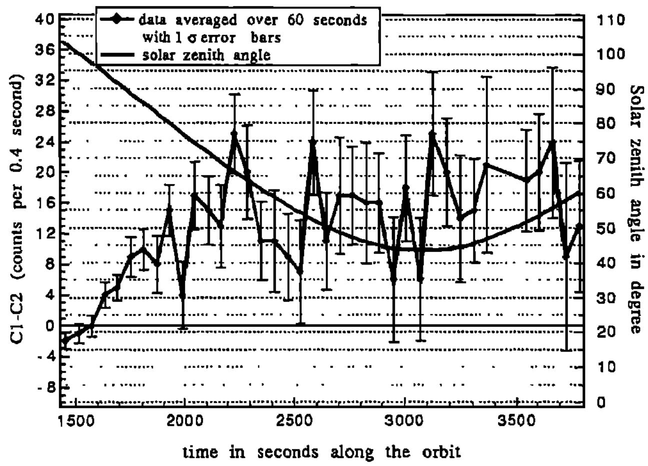

Fig. 5. Difference of counters $C_1 - C_2$ as a function of time (same time scale as in figure 4, same session). C_1 measures the signal with the H_2 cell on and the D_2 cell off whereas C_2 measures the signal with both cells activated. The difference $C_1 - C_2$ accounts for the fraction of the D Lyman α emission which is absorbed by the D_2 cell. The solar zenith angle, which varies between 43° and 100° here, has been added for comparison (right-hand scale).

seconds, along with the 1 σ statistical error bar. Data shown in figures 4 and 5 come from the same observation period and are representative of the scale of each signal. Typically the difference $C_1 - C_2$ is slightly more than 1 % of C_1 when the H_2 cell is activated, and about 0.1 % of C_1 when the H_2 cell is off. Since, for the moderate absorption power of the D_2 cell as calibrated on the ground with a deuterium resonance cell, about half of I_D should be absorbed, the average of 16 counts for $C_1 - C_2$, measured in the range $43° \leq \chi \leq 60°$ (figure 6), corresponds to I_D = 60 R within a factor of 2, in fair agreement with the model calculation which predicts 67 Rayleigh.

4. Data-model comparison for I_D as a function of solar zenith angle

In figure 6, we have averaged the data over almost 4 hours of nadir observation and plotted them as a function of χ. The right-hand scale is for the difference between counters 1 and 2 when the H_2 cell is on and is 20 times smaller than the left-hand scale, which has enabled us to plot both C_1 and C_2 data along with their difference in the same figure. The $C_1 - C_2$ curve, with the 1 σ statistical error bar, clearly shows the dependence of the nadir intensity on the solar zenith angle χ.

This curve is compared to a model calculation of I_D (solid line), adjusted to fit the data in the range $43° \leq \chi \leq 60°$. The model predicts 67 Rayleigh. The density distribution of D was assumed to be the one in figure 1, with no diurnal variation. I_D was computed as

$$I_D = 10^{-6} \int_0^{300} \varepsilon_D(z)\, e^{-\tau(z)}\, dz \qquad (2)$$

where the emissivity was computed in the appropriate spherical geometry (equation (1), which holds for plane parallel geometry, is no longer valid for $\chi \geq 80°$).

The relatively good agreement of the data and the model suggests that indeed the variation in the data is due, as in the model, to the progressive masking of D atoms by O_2 when χ increases, allowing a sounding of the region between 80 and 110 km of altitude as explained in section 2.

However, there may be also some diurnal variation of O_2 and of D which may also affect the variation of I_D with χ as suggested by the discrepancy between model and data in the range 90°-100°. A complete modeling is foreseen in the future, but is beyond the scope of the present paper.

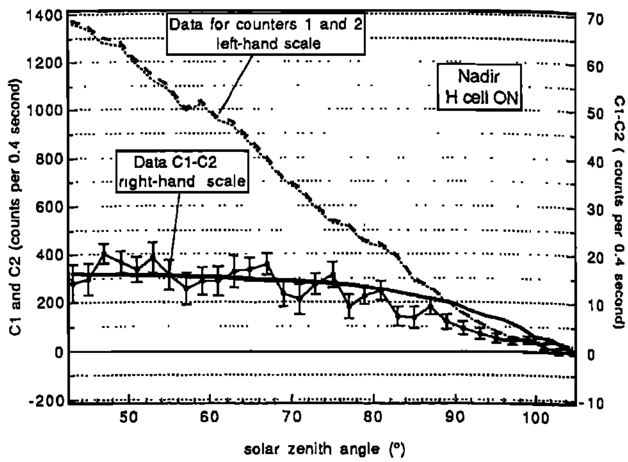

Fig. 6. Nadir data for difference of counters ($C_1 - C_2$) as a function of the solar zenith angle (right-hand scale) and nadir data for counters C_1 and C_2 (left-hand scale). The thick solid line shows nadir I_D computed by integration of the volume emission rate of figure 2 with extinction along the line of sight. The curve has been scaled to fit the data for χ between 43° and 60°.

5. Conclusion

We have shown here only a limited sample of the 103 hours of data collected during the *ATLAS* 1 mission. It will take some time to process this amount of data, but as we have already shown, here is an opportunity to get information about deuterium and hydrogen in the mesosphere.

The concentrations inferred from the nadir data will be compared to the profiles derived from limb observation data, which enables us to study both the mesosphere and the thermosphere thus bringing information on this important region of our atmosphere.

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References

Bertaux J.L., Goutail F., Dimarellis E., Kockarts G. & Van Ransbeeck E. 1984, First optical detection of atomic deuterium in the upper mesosphere from Spacelab 1, Nature 309, 771-773

Bertaux J.L., Le Texier H., Goutail F., Lallement R. & Kockarts G. 1989. Lyman α observations of geocoronal and interplanetary hydrogen from Spacelab 1: exospheric temperature and density and hot emission, Annales Geophysicae 7, (6). 549-564

Hunten D.M., Strobel D.F., 1974, Production and escape of terrestrial hydrogen, J. Atmos. Sciences, 31, 305-317

Lemaire P., Charra J.,Jouchoux A., Vidal-Madjar A., Artzner G.E., Vial J.C., Bonnet R.M. & Skumanich A. 1978, Calibrated full disk solar H Lyman α and Lyman β profiles, Astrop. Journal Letters, 223. L55-L58

Liu S.L., Donahue T.M., 1974, The aeronomy of hydrogen in the atmosphere of the Earth, J. Atmos. Sciences, 31, 1118-1136

Meier R.R., 1991, Ultraviolet spectroscopy and remote sensing of the upper atmosphere. Space Science Review, 58, 1-185

Moreels G., Mégie G., Vallace Jones A., Gattinger R.L., 1979, An oxygen-hydrogen atmospheric model and its application to the OH emission problem, J.A.T.P., 39, 551-570

Vidal-Madjar A. 1975, Solar Physics, 40, 65

Sharp W.E. & Kita D. 1987, In situ measurement of atomic hydrogen in the upper mesosphere, JGR 92, D4, 4319-4324

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