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A SEARCH FOR THE DEUTERIUM LYMAN-ALPHA EMISSION FROM THE ATMOSPHERE OF MARS

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ABSTRACT

Several High Resolution UV spectra of planet Mars were taken in May 1991 with GHRS, in an attempt to detect the presence of Deuterium atoms in the upper atmosphere of Mars by resonance scattering of solar Lyman alpha photons. The Hydrogen Mars Lyman alpha emission amounts to 8 kiloRayleigh, clearly distinguished from geocoronal emission at 25 kR. After subtraction of scattered light generated by the Echelle A grating, there is a small spectral feature remaining at the Deuterium resonance wavelength of 1215.33 Å, at the 2 sigma level above noise, with an intensity of 30 Rayleigh. The reality of this feature will be discussed, together with the significance of this intensity for the atmosphere of Mars.

1. SCIENTIFIC RATIONALE FOR DEUTERIUM OBSERVATIONS WITH HST

Among the three terrestrial planets with an atmosphere, only one (the Earth) has a large abundance water. Venus and Mars contain much less water, but it is still unresolved if they were formed with the same water abundance as the Earth and subsequently lost most of their water, or if they formed with initially less water abundance.

Deuterium is a potential tracer of the history of water on Venus and Mars, because of the differential escape mechanism. In the upper atmosphere, H and D atoms reach the exobase level (where there are no more collisions). Atoms with a velocity larger than the escape velocity will escape ; but because of the heavier mass of D atoms, a much smaller fraction of the Maxwell-Boltzmann distribution lies above the escape velocity.

Since the present (D/H) ratio in Earth sea water is equal to the one found in meteorites (1.6×10^{-4}), it is assumed that Earth has not lost a significant amount of water, and that this value is the original ratio for water in the three planets, $(D/H)_o$. The present Deuterium enrichment ratio α is defined as :

$$(D/H)_{now} = \alpha (D/H)_o \quad (1)$$

where $(D/H)_{now}$ is the ratio found in water vapour of Venus and Mars, which has been measured for Venus and Mars.

Equation (1) can be rewritten :

$$H_o = H_{now}\, \alpha \frac{D_o}{D_{now}} \quad (2)$$

in which H_o, H_{now} are the Hydrogen abundances (total content) at the planet formation and now, and the same for D_o and D_{now}. The ratio D_o/D_{now} is the Deuterium loss factor over the life of the planet.

Of course relation (2) applies to water, since H is mainly contained in water :

$$(H_2O)_o = (H_2O)_{now}\, \alpha \frac{D_o}{D_{now}} \quad (3)$$

Therefore, the original content of water $(H_2O)_o$ is the present content $(H_2O)_{now}$, multiplied by the enrichment ratio α (which is known: 120 for Venus, 6 for Mars), multiplied by the Deuterium loss factor $\frac{D_o}{D_{now}}$, which is totally unknown.

If no Deuterium ever escaped, the loss factor is unity, yielding a lower limit of original water abundance, which is only ≈ 3 meter for Venus (compared to 3 km for Earth) when $(H_2O)_{now}$, is computed from measured H_2O profiles (Donahue and Hodges, 1992). If there was a large escape of Deuterium, then there could have been much more water in the beginning.

The Deuterium loss factor is the Deuterium escape rate integrated over the life of the planet. The escape rate is of course proportionnal to D concentration in the upper atmosphere. A measurement of Deuterium in the upper atmosphere of Venus and Mars could help to estimate the present escape rate from these planets, a condition necessary to estimate the total Deuterium loss factor (but may be not sufficient).

The atomic Hydrogen abundance is known in the upper atmosphere of these planets; and if the $(D/H)_{now}$ measured in H_2O in the lower atmosphere were conserved all through the atmosphere, it would be trivial to estimate the D abundance in the upper atmosphere. Indeed, Spacelab-1 first observations of atomic Deuterium in Lyman α in the upper atmosphere of the Earth (Bertaux et al, 1984) indicated a similar D/H ratio around 100 km as in sea water.

This finding, coupled to the large D/H ratio of 1.5×10^{-2} found in the water of Venus by Pioneer Venus mass spectrometer (Donahue et al, 1982) pressed us to attempt with IUE a measurement of D Lα emission. The result was surprising: no D Lyman α emission was detected, yielding a D/H ratio $< 2 \times 10^{-3}$ in the upper atmosphere of Venus, in contrast with the 1.5×10^{-2} ratio found earlier (Bertaux and Clarke, 1989). This may indicate that, in contrast to the Earth, there was some differenciation between the lower and the upper atmosphere of Venus.

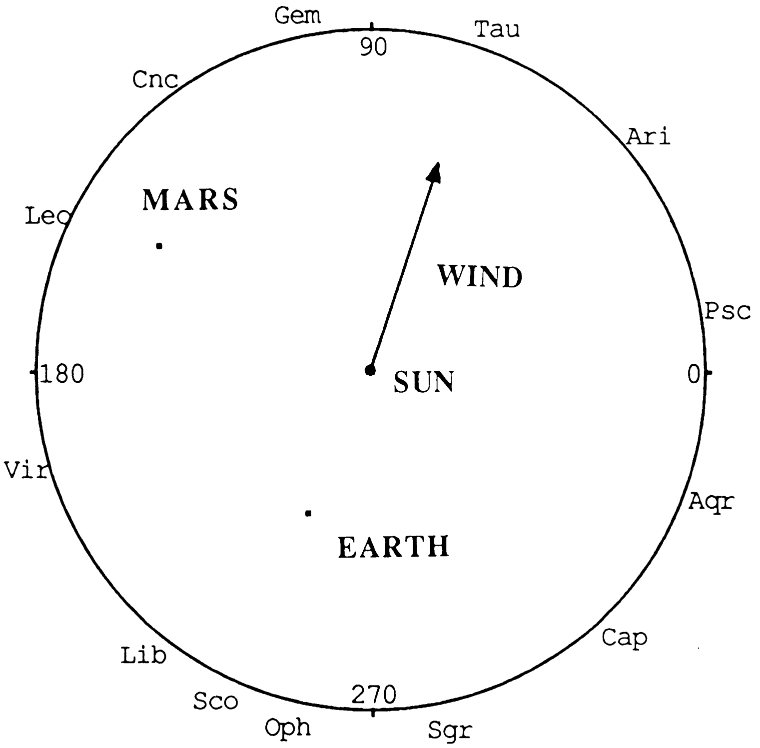

Figure 1. Relative position of Sun, Mars and the Earth at the time of HST observations in the ecliptic plane. The interstellar wind is blowing through the solar system from the direction 252° in ecliptic longitude, and +6° in ecliptic latitude, yielding the observed Doppler shift.

The next logical step was to use HST/GHRS, in order to confirm the low D Lyman α of Venus, and to attempt detection on Mars. Since then, HDO was observed in the infra-red both for Venus and Mars. De Bergh et al (1991) confirmed a strong enrichment of Deuterium for Venus (120±40) and Owen et al (1988) and Mumma et al (1989) measured an enrichment ratio of 6 for planet Mars. Our initial proposal for Cycle 1 included Venus, but was withdrawn because of solar angle constraints. Therefore, Lyman alpha Deuterium observations were planned for Mars, with the double objective: to compare the D/H ratio in the upper atmosphere to the one measured in the lower atmosphere (search for differenciation) and to estimate the present Deuterium escape rate, as an input to the estimate of the integrated loss factor for Mars and original water content. Ultimately, it would have to be explained why differenciation of D/H was different in the three telluric planets.

2. HST/GHRS CYCLE 1 OBSERVATIONS OF MARS AT LYMAN α

Our Mars programme, which was accepted for Cycle 1, was executed on 21-22-23 May 1991, actually before the start of Cycle 1, because at that time Mars was rapidly receding from Earth and approaching the limit of the solar angle. The relative position of Earth, Mars and the Sun are shown on figure 1. Mars was at 56° from the Sun, and its diameter was 4.7 arcsec, seen from Earth, with a phase angle of 34°. Five orbits were devoted to the measurement of Lα emission from the disc of Mars, and two orbits were pointed 1 arcmin away from Mars (at a smaller solar angle), in order to get spectra of the geocorona alone for subtraction of the Mars + geocorona observations. For a combination of high resolution and large throughput, the Large Science Aperture (LSA, 2 x 2 arcsec) and Echelle A mode of GHRS was used.

Pointing a moving target is not a simple matter with HST. The pointing was made with two guiding stars (changing at each orbit). In order to have a better chance to point at the center of Mars, a linear motion was given to HST, along the predicted track of Mars, but with a slightly lower rate, beginning about 1 arcsec ahead of the computed disc center of Mars and finishing about 1 arcsec behind at the end of the 20 minutes exposure.

Since the disc of Mars (and *a fortiori* the geocorona) is an extended source larger than the LSA aperture, the calibration factor at Lα established for HST prior to flight should be still valid, even with the extended PSF resulting of the spherical aberration of the primary.

The monochromatic image at Lα of the LSA should be spread over 8 diodes (out of the 512 diodes of the Digicon), corresponding to 0.1 Å, since the dispersion of Echelle A is of 0.0128 Å per diode.

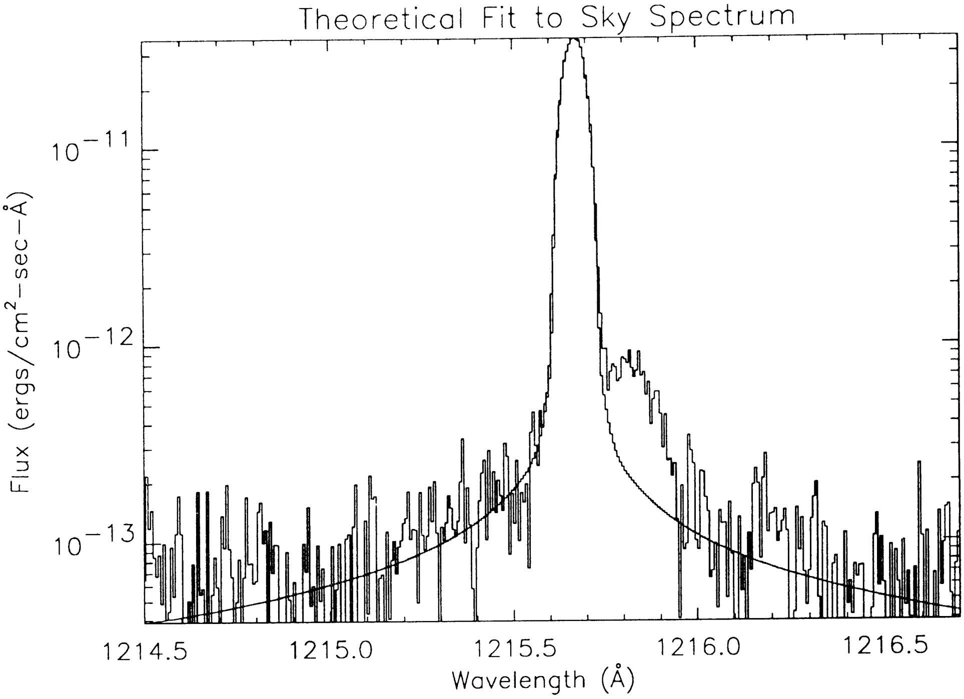

Figure 2. Spectrum of the geocoronal HLα emission obtained when the line of sight was pointing near Mars, but with an offset of 1 arcmin. The width is due to the finite size of the LSA. The solid line is a model of the scattered light based on previous work and adjusted to observations. The interplanetary line is quite prominent on the red side of the line.

On figure 2 is a plot of all "sky" data taken when Mars was not in the F.O.V., because of the 1 arcmin offset. The four individual spectra (taken with FPSPLIT mode) were added together after appropriate small wavelength shifts. The main feature is the strong geocoronal emission, and a wavelength scale was obtained by assigning to the center of this feature the wavelength of the H Lα resonance, namely 1215.671 Å. The high quality of GHRS is demonstrated by the fact that the interplanetary emission is clearly seen on the right side of the geocoronal feature, even with a total of only 20 minutes exposure. The observed red

Doppler shift is what is expected from the geometry of the observations at this particular time of the year and celestial direction of sight.

After subtraction of a constant level of Dark Counts estimated from counts in the 4 corner diodes at the extremity of the Digicon, there is a component of scattered light from the Echelle A grating, extending on both sides of the geocoronal line. The solid line is a model of the scattered light, built on estimates given by Denis Ebbets (Cardelli et al, 1990) adjusted to our observations.

The geocoronal intensity found for the four individual 5 min exposures sky spectra were compared to a model of the geocorona, taking into account the position of HST on its orbit. The intensity decrease observed with time along the orbit is perfectly reproduced by the model (not shown here). The measured average intensity is 25 kiloRayleigh.

On figure 3 is plotted the sum of all Mars spectra taken on the various orbits, averaged together to give a flux in ergs/cm^{2}sec Å. The geocorona at 1215.671 Å is still the largest feature observed in the spectrum, but the H Lα emission of Mars is quite obvious, as a shoulder found on the red side of the geocoronal H Lα. The interplanetary Lα feature marked ISM is much smaller than on figure 2, because in this case the integration of the ISM emission along the line of sight stops at the distance of Mars.

Given the epoch of observation, there is a velocity of Mars of +13.54 km/s corresponding to a Doppler shift of the Martian Lα emission in respect to the geocoronal emission, of + 0.055 Å.

Therefore, the D Lα emission from Mars should lie at 0.330 Å shorter the Mars H Lα, or at 0.275 Å shorter than the geocoronal emission, and is indicated on figure 3 with a question mark. At the altitude of HST, we do not expect any substantial contribution of terrestrial D Lα emission since most of the emission is concentrated in the mesosphere and lower thermosphere (Bertaux et al, 1992) below ≈ 150km of altitude.

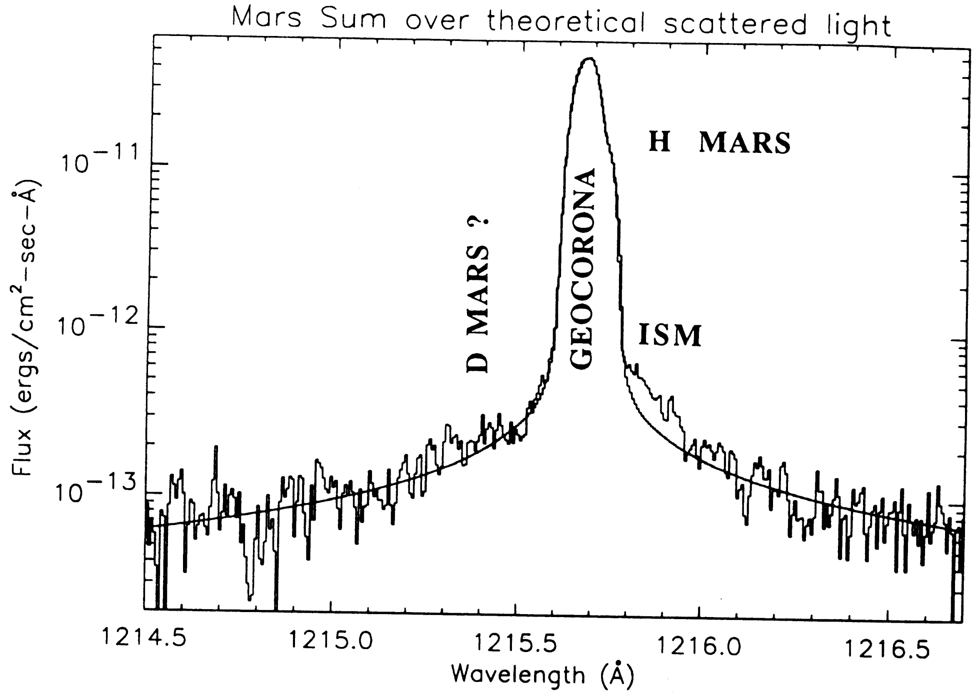

Figure 3. Spectrum obtained by summing together all Mars pointing observations. The H Lα Mars emission is clearly seen as a shoulder to the geocorona line. The position of D Lα Mars is indicated with a question mark. The solid line is a model fit to the scattered light from both geocorona and H Mars.

After subtraction of the geocoronal emission from the Mars + geocorona emission, the Mars H Lα emission not shown here was found to be 8 kR, slightly more than the 5 to 6 kR measured by Mariner 9 UV spectrometer in 1971 and reported by Anderson (1974).

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Finally, from the spectrum of figure 3 was subtracted a computed synthetic spectrum containing the theoretical fit to the geocoronal spectrum and its proper scattered light, plus the scattered light model corresponding to the Mars H Lα emission. The data were then smoothed with an 8 point running mean and plotted in a linear scale on figure 4. A synthetic spectrum of a Mars D Lα emission of 30 Rayleigh is shown as a dashed line, which fits quite well a peak in the resulting spectrum at 1215.396 Å, about twice as high as the other peaks in the spectrum which height may be used as a measurement of the noise level. However, there is also another peak feature, even larger, at 1215.30Å, that cannot be explained, and the "Deuterium" peak should be attributed cautiously to atomic Deuterium in the upper atmosphere of Mars.

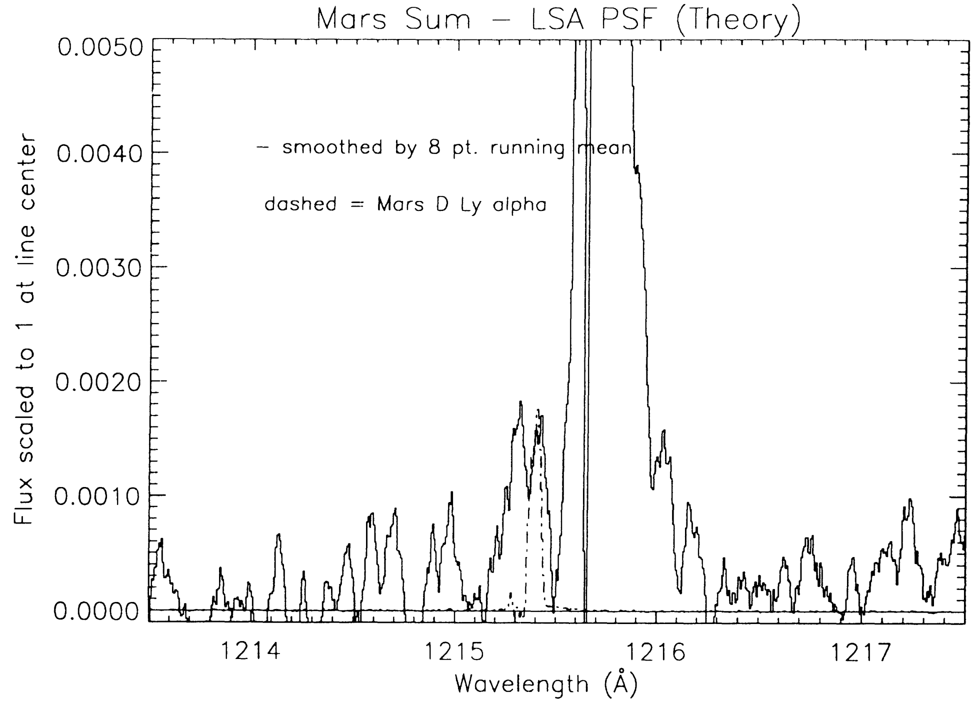

Figure 4. Difference between data and the model fit of figure 3, normalized to data at line center and after smoothing. The dashed line is a synthetic line at the position of D Lα Mars.

3. DISCUSSION

Whatever is the assignment of this Deuterium peak (marginal positive detection, or upper limit), it can be discussed in terms of D/H ratio. The intensity of this peak is 30 Rayleigh, to be compared with the 8 kR of H Lα from Mars. This ratio of intensities of $\approx 4 \times 10^{-3}$ can be converted into a D/H ratio of column densities of D atoms and H atoms above the 80 km penetration level in the atmosphere of exciting Lα solar photons. The optical depth for pure absorption by CO_2 is 1.42 at 80 km (Strickland and Anderson, 1973).

Taking a 1 AU solar flux of 4×10^{11} phot.cm^{-2} s^{-1} Å at the center of the line (high solar activity at the time of the observations), and an equal solar flux at the excitation wavelength of Deuterium, the excitation factor for D atoms at the distance of Mars will be: 1.1×10^{-3} scattered photons per second per atom. Deuterium is optically thin and the 30 Rayleigh intensity converts into a Deuterium column density N_D :

$$4\pi I_D \text{ (Rayleigh)} = 10^{-6} g \times N_D$$

$$N_D = 2.7 \times 10^{10} \text{ atoms/cm}^2 \text{ above 80 km of altitude.}$$

The corresponding estimate for H column density above 80 km is somewhat more complicated, because the optical thickness for H is more than unity. According to the analysis of Anderson (1974), this optical thickness is $\tau = 5\ (+5, -1)$ at line center, which converts into a Hydrogen column density $N_H = 1.6\ (+1.6,-0.3)\ 10^{13}$ H atoms cm^{-2}. As mentionned before, there is some indication that the observed HST H Lα of Mars was higher than at the time of Mariner 9. Since the GHRS calibration factor may be somewhat uncertain for extended sources and with the aberrated pSF, at this stage of the analysis we prefer to rely on the Mariner 9 estimate for the H column density.

Therefore, the ratio of D/H column densities above 80 km in the atmosphere of Mars as determined from these HST observations is 1.7×10^{-3} or lower. It is still quite compatible with the lower atmosphere raio of 10^{-3} determined from HDO/H_2O observations in the Infrared by Mumma et al (1989), at variance with the case of Venus, where D Lα observations failed to show D atoms in the upper atmosphere, revealing a decrease of D/H ratio from the lower to the upper atmosphere of a factor of 8. (Bertaux and Clarke, 1989). The mechanism for such a differenciation remains to be elucidated.

4. CONCLUSION

Unfortunately the DLα emission measured with HST at 30 Rayleigh for Mars remains a marginal detection, being at twice the average noise (2σ signal). However, it compares quite favorably with the 300 R upper limit that we could derive with IUE on Venus and shows the high potential of HST/GHRS. The main limitation for this kind of observations remains the scattered light from the grating. For these measurements obtained during Cycle 0, the observing conditions were not optimal, because the data were taken when the HST spacecraft was on the dayside of the Earth, yielding a high geocoronal Lα emission of about 25 kR and a corresponding high scattered light. In the future,when side 1 of GHRS may be used again, observations could be planned at opposition, or before. Near opposition, the geocoronal intensity will be much lower (≈ 2 kR), but the absence of Doppler shift will make both H Lα line of Earth and Mars coïncident. Still, the H Lα Mars could be derived by subtraction of observations of geocorona only.

Alternately, observations may be conducted before opposition, to have the H Lα Mars on the blue side of the geocorona line, which would allow to place the Mars D Lα line further away from the geocoronal line. The stray light may be reduced by a factor of three, which would allow to conclude on the presence or not of D/H differenciation in the atmosphere of Mars.

Even with this limited observation, further modelling of the atmosphere of Mars will allow to derive more precise D/H ratio, or upper limit, in the upper atmosphere of Mars.

The observation of the interplanetary/interstellar wind will be interpreted in another paper. However, we would like to point out that with only 40 minutes of integration time, we obtained a very decent signal. As demonstrated by Lallement et al (1992), the particular shape of the interplanetary emission is sensitive to the effect of the heliopause on the flow of interstellar hydrogen. Therefore, accurate observations with HST might reveal the very existence of the heliopause boundary between the interstellar plasma and the heliosphere for the first time, and this is one more reason to put back in operation Side 1 of GHRS, with proper hardware and/or software refurbishment.

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REFERENCES

Anderson, D.E., Jr., Mariner 6,7 and 9 Ultraviolet Spectrometer Experiment : Analysis of Hydrogen Lyman Alpha Data, J. Geophys. Res., 79, 1513-1518, 1974

De Bergh, C., B. Bēzard, T. Owen, D. Crisp, J.P. Maillard and B.L. Lutz, Deuterium on Venus : Observations from Earth, Science, 251, 547-549, 1991

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

Bertaux, J.L., E. Quemerais, F. Goutail, G. Kockartz, B. Sandel, Observations of Atomic Deuterium in the mesosphere with Atlas-1, to be submitted to GRL, 1992

Bertaux, J.L. and J.T. Clarke, Deuterium content of the Venus atmosphere, Nature, 338,567-568,1989

Cardelli, J.A., D. Ebbets, B. Savage, Scattered light in the Echelle modes of GHRS aboard HST. I. Analysis of prelaunch calibration data., Ap. J., 365, 789 - 802, 1990

Donahue, T.M. and R.R. Hodges, Jr : Past and Present Water Budget of Venus, J. Geophys. Res., 97, 6083-6091, 1992

Lallement, R., Y. Malama, E. Quemerais, J.L. Bertaux, N.A. Zaitsev, Interplanetary Lα Spectra as a diagnostic of the local interstellar plasma density : the Baranov two-shocks heliosphere case, Astrophys.J., in press, Sept. 1992

Mumma, M I, G. Bjoraker, H.P. Larson, Bull. of the American Astron. Society, 21, p. 991, 1989 (abstract only)

Owen, T., J.P. Maillard, C. de Bergh, B. Lutz, Deuterium on Mars : The abundance of HDO and the value of D/H, Science, 240, 1767, 1988

Strickland, D.J. and D.E. Anderson, Jr., Theoretical Emergent Lyman-alpha Intensities from Mars, J.G.R., 78, 6491-6495, 1973