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LETTER

Letter to the Editor

ORFEUS II Echelle spectra: molecular hydrogen at high velocities toward HD 93521

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Abstract. Absorption lines of interstellar molecular hydrogen in the far ultraviolet (FUV) have been observed in the spectrum of the O9.5 halo star HD 93521, located some 1500 pc from the Galactic plane. During the second *ORFEUS-SPAS* mission a spectrum with the Echelle spectrometer has been recorded with a total integration time of 1740 s. The resolution achieved was about $\lambda/\Delta\lambda \geq 10.000$ with a signal-to-noise ratio of up to 25. For the first time two components of molecular hydrogen have been observed in absorption at velocities of $\simeq -12$ km s^{-1} in the Galactic disk and at $\simeq -62$ km s^{-1} located presumably in the Galactic halo. The column densities derived from a standard curve of growth analysis were found to be $N(\mathrm{H_2}) = 10^{17.0}$ cm^{-2} for the disk component and $N(\mathrm{H_2}) = 10^{14.6}$ cm^{-2} respectively for the component located in the Galactic halo.

Key words: stars: individual: HD 93521 – ISM: abundances – ISM: molecules – ultraviolet: ISM

1. Introduction

Interstellar molecular hydrogen can be investigated in the near infrared in emission and in the far ultraviolet (*FUV*) in absorption. The *FUV* spectroscopy offers the possibility to investigate the cool component of the diffuse *ISM* in which the H_2 molecules play a dominant role. The spectral range between 910 and 1150 Å contains the absorption transitions of the Lyman and Werner bands of molecular hydrogen. Since the *Copernicus* satellite some 20 years ago (Spitzer et al. 1973, 1974) no high resolution spectroscopy in the *FUV* could be done. A comprehensiv survey of interstellar molecular hydrogen as observed with the *Copernicus* satellite is given by Savage et al. (1977).

With the *ORFEUS-SPAS II* mission launched aboard the US Space Shuttle *COLUMBIA* in Nov. 1996, it was possible to gather Echelle spectra with a high resolution of $\lambda/\Delta\lambda \geq 10.000$ of much fainter objects than observable with *Copernicus*. The *ORFEUS* telescope itself is described in detail by Krämer et al. (1988) and Grewing et al. (1991). An instrument description of the *ORFEUS II* Echelle spectrometer as well as its performance and the data reduction are given by Barnstedt et al. (1999). Meanwhile the detection of H_2 absorption with the *ORFEUS* Echelle spectrometer was reported for the SMC by Richter et al. (1998) as well as for the *LMC* by de Boer et al. (1998). Furthermore molecular hydrogen in the Galactic halo was observed with *ORFEUS*by Richter et al. (1999) in a high-velocity cloud.

The high latitude Galactic halo star HD 93521 was one of the PI targets chosen to be observed for possible H_2 absorption. The complete spectrum of HD 93521 is given by Barnstedt et al. (2000). Savage et al. (1977) reported an upper limit of $N(\mathrm{H_2}) \leq 10^{18.54}$ cm^{-2} for this target with a lower limit estimated to be 2.7 dex smaller. These authors could not detect other components at higher velocities presumably because the sensitivity of the *Copernicus* spectrometer was too low for such a weak component.

On the other hand it was well known from high resolution ground based measurements that the interstellar Ca II-line shows a complex profile toward HD 93521: Münch & Zirin (1961) found two main components (out of four altogether) at velocities of -12 km s^{-1} and -56.3 km s^{-1} indicating at least one intermediate velocity cloud (*IVC*). Later on Rickard (1972) reported a good correlation between the Ca K-lines in front of HD 93521 to the profile of the hydrogen 21 cm lines. Spitzer & Fitzpatrick (1993) finally deduced from *HST* observations with the high resolution *GHRS* Echelle spectrometer nine different clouds or filaments toward HD 93521 for the less ionized species like Si II, S II etc. with heliocentric velocities ranging from -66.3 km s^{-1} to 7.3 km s^{-1} and even one more component when fitting radio 21 cm observations of neutral hydrogen.

This paper presents the detection of molecular hydrogen in absorption in the Galactic disk as well as in an *IVC* in the Galactic halo. Following the arguments and findings by Münch & Zirin (1961), Rickard (1972), Albert (1983) and Danly et al. (1992) we designate absorption features occuring at radial

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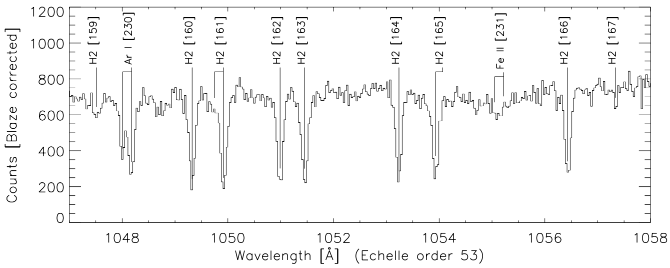

Fig. 1. A portion of the *ORFEUS*-Echelle spectrum is shown near 1053 Å without any smoothing. Besides Ar I and Fe II the H_2 absorption lines for the transitions R0 to P3 of the Lyman series 4-0 (numbers 160 to 166) are very pronounced. The vertical markings indicate the radial velocities of -12 km s^{-1} and -62 km s^{-1} for these lines. The numbers in brackets refer to the line identifications for HD 93521 given by Barnstedt et al. (2000)

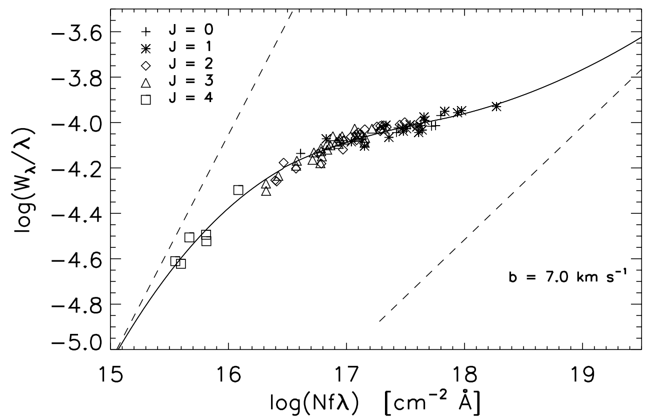

Fig. 2. The H_2 lines of the Galactic disk components with radial velocities $\simeq -12$ km s^{-1} were fitted to a single curve of growth, indicating $b \simeq 7$ km s^{-1}. The column densities for the levels J=0–4 are given in Table 1. The dashed lines represent the linear part and the square root section of the curve of growth

velocities near -12 km s^{-1} as produced by gas components belonging to the Galactic disk and the absorption features near -62 km s^{-1} as gas belonging to the Galactic halo.

2. Observations and data reduction

HD 93521 is a high galactic latitude halo star located at l = 183.1°, b = 62.1°, d = 1.64 kpc. The star is of spectral type O9.5Vp, has V = 7.04 mag and $E(B-V)$=0.02 mag (Diplas & Savage, 1994). These authors determined the total interstellar neutral hydrogen column density from Ly-α absorption gained with the *IUE* satellite as N(H I) = $10^{20.11}$ cm^{-2} toward HD 93521, in excellent agreement with the sum of the 10 different velocity components published by Spitzer & Fitzpatrick (1993) from H I 21 cm observations.

The total observing time with the *ORFEUS II* Echelle spectrometer was 1740 s in two pointings during two successive orbits. Both spectra were integrated separately on board and later on coadded applying the standard extraction procedure described by Barnstedt et al. (1999). The data in the different echelle orders were blaze corrected, after the subtraction of the background caused in large part by straylight of the echelle grating. Due to the fact that HD 93521 was not absolutely centered in the entrance diaphragm an additional radial velocity correction of -10 km s^{-1} was applied to the spectrum (see Barnstedt et al. 2000).

3. H_2 column density in the Galactic disk component

A closer inspection of the absorption line profiles from the Echelle spectrometer reveals immediately the presence of two components with different radial velocities as shown in Fig. 1 for the Ar I λ 1048.2 line. The same holds for N I and almost all of the less ionized species like Si II, S II and Fe II (see also Barnstedt et al. 2000). Both components are separated by $\simeq 50$ km s^{-1} and show almost comparable intensities for the atoms or ions mentioned above.

The H_2 absorption lines of the Lyman (4-0)-band from R0 to P3, shown in Fig. 1 also, are very sharp and pronounced. The FWHM values for some H_2 absorption lines are sometimes as small as 100 mÅ. The equivalent widths W_λ of the lines were determined either directly from the observations in the standard manner or by a Gaussian fit of the line or if possible by both methods. The f-values for the further analysis were taken from Morton & Dinerstein (1976) for the H_2 transitions and for the atomic lines from the compilation of Morton (1991).

Table 1. H_2 column densities toward HD 93521. Galactic disk component near -12 km s^{-1} (for uncertainties see error bars in Fig. 3)

Rotation level J	$\log N(J)$	b-value [km s^{-1}]	Number of lines used
0	16.33	7	8
1	16.72	7	18
2	16.07	7	26
3	15.90	7	28
4	14.56	7	6

Furthermore, curves of growth have been constructed for each of the absorptions by the 5 rotational states (J=0–4) for the Galactic disk component located at radial velocities around -12 km s^{-1}. The sample of the $\log(W_\lambda/\lambda)$-values for each rotational level J has been shifted horizontally to give a fit to a theoretical single-cloud curve of growth as a function of $N(J) f \lambda$. Because the curve of growth just begins to depend slightly on the damping constant γ for the three righthand points in Fig. 2, γ has been chosen to γ = 12 10^8 s, a mean value for these three points. The best fit for the 5 rotational states was obtained with b = 7 km s^{-1} and is shown in the empirical curve of growth in Fig. 2. The column densities $N(J)$ obtained in this way can be found in Table 1. The uncertainties in the column densities are based on the respective determinations of the equivalent widths as well as on the quality of the fits to the curve of growth. They range from 0.25 to 0.45 dex and are shown in Fig. 3. The total logarithmic column density for these lowest 5 rotational levels was found to be $\log N(H_2)$ = 17.0 ±0.4 for the Galactic disk component.

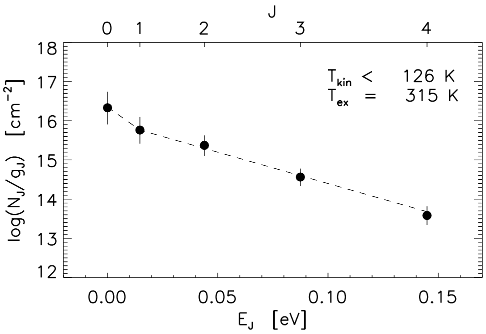

Fig. 3. The H_2 column densities of the Galactic disk component divided by their statistical weights are plotted against their excitation energy for the levels J=0–4. The higher levels were fitted to an equivalent excitation temperature of $\simeq 315$ K. For the two lower levels the kinetic excitation temperature is < 126 K (see Sect. 3). The error bars shown are based on the uncertainties in the curve of growth fits

In order to get information about the mean excitation temperature in the Galactic disk components, we fitted the population densities by a Boltzmann distribution, as shown in Fig. 3. The column densities $N(J)$ divided by their statistical weigths g_J are plotted against the excitation energy E_J. For the two lower rotational states we derive an upper limit for the excitation temperature $T_{0,1} < 126$ K for the disk gas. This must be an upper limit because the column density of the J=1 level fits very well to a Boltzmann distribution for the levels J=1–4 (see below). Assuming that the collisional excitation to level J=1 amounts to only 10% of the observed column density (in view of the good fit for J=1–4) one finds $T_{0,1} \simeq 47$ K. This value is in the range of excitation temperatures reported by Savage et al. (1977) for general galactic gas.

For the rotational levels $1 \leq J \leq 4$ we derive a mean excitation temperature of $\simeq 315$ K, indicating that moderate UV pumping is responsible for the excitation of these states (Spitzer & Zweibel 1974). The results of Fig. 3 indicate furtheron that these ortho and para levels of H_2 are in thermal equilibrium in the Galactic disk gas.

Although a mean excitation temperature of $\simeq 290$ K can be fitted for all rotational levels as indicated by the data and their uncertainties, we still believe that the bend in the excitation temperature at the J=1 level is real for the following reasons: The major part in the uncertainty given is due to the uncertainty of the continuum determination in evaluating the corresponding equivalent widths. Because the values for J=0 and J=1 are located on the flat part of the curve of growth, the resulting absolute errors are the largest ones for these two levels. On the other hand the R0 and R1 absorption features in the different Lyman-bands are separated by a small wavelength difference (< 1 Å) only. Most of these equivalent widths have been determined with a similar or even the same value for the adopted continuum. This implies that the ratio between the column densities for the rotational levels J=0 and J=1 should be real and thus that the bend at J=1 in Fig. 3 leading to the two different excitation temperatures is real, too.

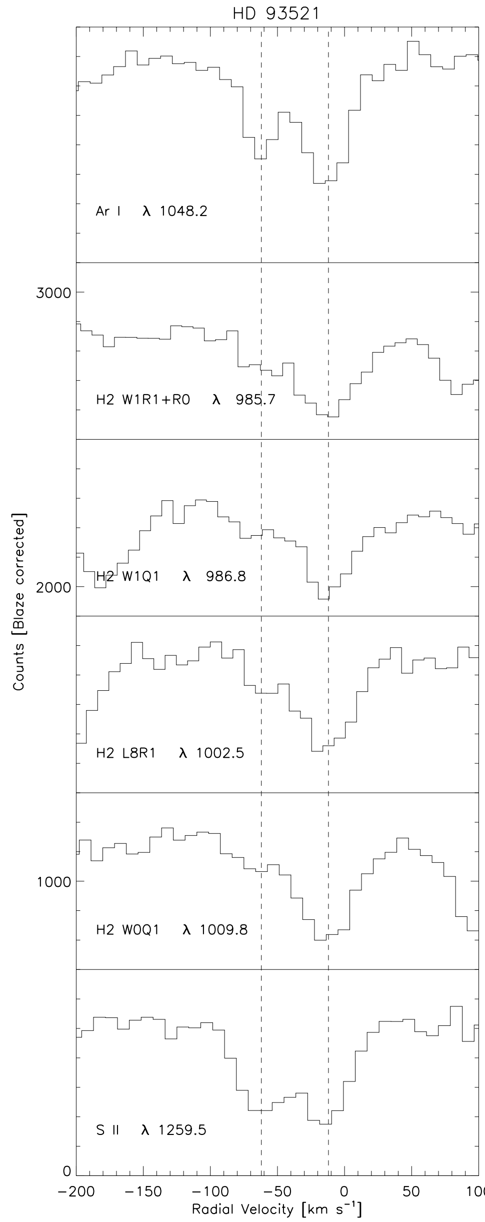

Fig. 4. Radial velocity plots for Ar I (top) and S II (bottom) together with the four H_2 absorption lines shown, indicate two radial velocity components at $\simeq -12\,\mathrm{km\,s^{-1}}$ and at $\simeq -62\,\mathrm{km\,s^{-1}}$ (vertical dashed lines). The x-axes of the plots correspond to zero counts for all the lines shown. The two velocity components are attributed to gas belonging to the Galactic disk and to the Galactic halo, respectively

4. H_2 column density in the Galactic halo component

With the *ORFEUS II* Echelle spectrometer it was possible for the first time to observe H_2 absorption components at higher velocities toward HD 93521. A comparison for some H_2 absorption features in the rotational level J=1 with Ar I (see also Fig. 1) and a typical S II line is shown on a radial velocity scale in Fig. 4. These unsmoothed data show convincingly the presence of a higher velocity component shifted by about $-50\,\mathrm{km\,s^{-1}}$ against the Galactic disk component discussed above. Altogether for six

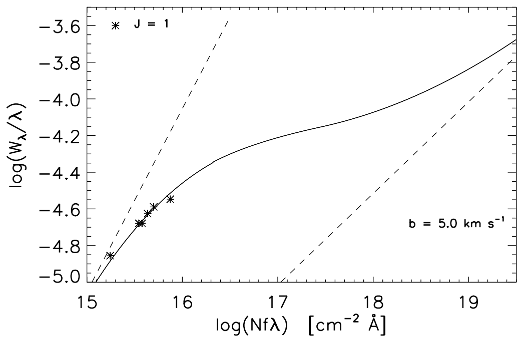

Fig. 5. H_2 absorption line components near $\simeq -62\,\mathrm{km\,s^{-1}}$ of the rotational level J=1 were fitted to the indicated curve of growth

Table 2. Equivalent widths for rotational level J=1. Galactic halo component near $-62\,\mathrm{km\,s^{-1}}$ (* 6 mÅ possible contribution from L11 P5 disk gas subtracted)

Transition	Wavelength [Å]	Equiv. width [mÅ]	f-value
L4 R1	1049.958	22	0.0160
L7 R1	1013.434	24	0.0205
W0 Q1	1009.772	26	0.0238
L8 P1	1003.304	14	0.0084
L8 R1	1002.457	21	0.0181
W1 Q1	986.798	28*	0.0364

J=1 features the corresponding equivalent widths were determined using a multi-Gaussian fit with linear continuum. The results are shown in Table 2. The *IVC* component of the W1 Q1 line in Fig. 4 might be contaminated by the Galactic disk component of the L11 P5 line centered at $-97\,\mathrm{km\,s^{-1}}$. A maximal contribution of $W_\lambda = 6$ mÅ from the latter has been subtracted from the W1 Q1 component. The equivalent widths of Table 2 have been fitted to a curve of growth as shown in Fig. 5 with a b-value of $\simeq 5\,\mathrm{km\,s^{-1}}$. The resulting logarithmic column density is $\log N(J{=}1) = 14.32$ with an uncertainty of ± 0.25 dex, the latter arising in large part from the errors made in determining the equivalent widths.

In the rotational level J=2 just one line exhibits an absorption feature near $-62\,\mathrm{km\,s^{-1}}$ above our detection limit. The equivalent width $W_\lambda \leq 16$ mÅ of this W2 R2 line (965.793 Å, $f = 0{,}0323$) leads to a value of $\log N(J{=}2) \simeq 13.88$ applying the curve of growth shown in Fig. 5. With this value and the population density for rotational level J=1 we calculate an excitation temperature $T_{1,2} \simeq 800$ K. This value must be regarded as an upper limit.

The fact that comparable absorption features for the J=0 rotational level in the Lyman-bands have not been observed implies a lower limit for the corresponding excitation temperature. Assuming again a Boltzman distribution for the population densities of these rotational levels an excitation temperature of 300 K leads to a logarithmic column density $\log N(J{=}0) \simeq 13.6$ and therewith to equivalent widths below 10 mÅ, and thus below the detection limit of the *ORFEUS* Echelle spectrometer. The stronger R0 components of the Werner bands could not be used for this evaluation because they are superimposed by the corresponding R1 components. In the W1-0 band the wavelength difference of both components is 19 mÅ, corresponding to about 0.6 electronic pixel. Within the above excitation temperature range we estimate the total logarithmic column density of molecular hydrogen to be $\log N(H_2) = 14.6 \pm 0.35$ for the *IVC* located in the Galactic halo toward HD 93521.

5. Concluding remarks

The *ORFEUS FUV* spectrum of HD 93521 shows absorption by interstellar H_2 at two radial velocity components around $-12\,\mathrm{km\,s^{-1}}$ and $-62\,\mathrm{km\,s^{-1}}$. The hydrogen fraction in its molecular form is 0.0025 for the Galactic disk gas and about 190 times smaller for the Galactic halo component. These calculations are based on the H I column densities reported by Spitzer & Fitzpatrick (1993). Attributing their velocity components 1-4 (-66.3 to $-38.8\,\mathrm{km\,s^{-1}}$) as H I gas belonging to the Galactic halo we get $\log N(\mathrm{H\,I})_{\mathrm{halo}} = 19.69$ and $\log N(\mathrm{H\,I})_{\mathrm{disk}} = 19.88$ from the other 6 velocity components. The estimated range for the excitation temperature indicates that UV pumping also takes place in the gas of the *IVC* in the Galactic halo.

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