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LETTER

Letter to the Editor

ORFEUS II echelle spectra: Detection of H_2 absorption in SMC gas

P. Richter[1], H. Widmann[2], K.S. de Boer[1], I. Appenzeller[3], J. Barnstedt[2], M. Gölz[2], M. Grewing[4], W. Gringel[2], N. Kappelmann[2], G. Krämer[2], H. Mandel[3], and K. Werner[2]

[1] Sternwarte, Universität Bonn, Auf dem Hügel 71, D-53121 Bonn, Germany
[2] Institut für Astronomie und Astrophysik, Abteilung Astronomie, Universität Tübingen, Waldhäuserstrasse 64, D-72076 Tübingen, Germany
[3] Landessternwarte Heidelberg, Königstuhl, D-69117 Heidelberg, Germany
[4] Institut de Radio Astronomie Millimétrique (IRAM), 300 Rue de la Piscine, F-38406 Saint Martin d'Hères, France

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Abstract. We present a study of H_2 in the SMC gas, based on Far UV spectroscopy in the line of sight to the SMC star HD 5980. 17 absorption lines from the Lyman band have been analysed. Our line of sight crosses two clouds within the SMC. We detect a cool molecular component near +120 km s^{-1}, where the H_2 from the lowest 3 rotational states ($J \leq 2$) is found. For this cloud we derive an excitation temperature of $\simeq$ 70 K, probably the kinetic temperature of the gas. Another SMC component is visible at +160 km s^{-1}. Here we find unblended H_2 absorption lines from levels $5 \leq J \leq 7$. For this component we obtain an equivalent excitation temperature of > 2350 K and conclude that this cloud must be highly excited by strong UV radiation from its energetic environment.

Key words: space vehicles .- ISM: molecules – galaxies: ISM – Magellanic Clouds: SMC – stars: individual: HD 5980 – ultraviolet: ISM

1. Introduction

Investigations of interstellar molecular hydrogen only are possible in the near IR in emssion and in the Far UV in absorption. The *Copernicus* has been the first satellite which was able to resolve UV absorption lines from galactic H_2 in the range of 900 to 1200 Å, and most of our knowledge about the physics of interstellar H_2 is based on studies with this instrument (Spitzer et al. 1974). In contrast to observations in the near IR, FUV spectroscopy offers the possibility to investigate also the cool component of the gas in which the H_2 molecule likely is the dominant constituent.

More than twenty years after the first results of the *Copernicus*, the *ORFEUS* FUV telescope allows the measurement of H_2 in all rotational states, not only in our own galaxy, but also in the interstellar matter of the two Magellanic Clouds. This is of great importance because of the lower metal content and different gas to dust ratio in the Magellanic Clouds (see Koornneef 1984). The *ORFEUS* 1m-telescope was launched for its second mission in Nov./Dec. 1996 with the *ASTRO-SPAS* space shuttle platform (Krämer et al. 1990). Its two alternately operating spectrographs work in different wavelength ranges with different resolutions. The UCB spectrograph has a spectral resolution of $\lambda/\Delta\lambda \sim 5 \cdot 10^3$ in a wavelength range from 300 to 1200 Å (Hurwitz et al. 1998). The echelle spectrograph operates between 912 and 1410 Å with a spectral resolution of $\lambda/\Delta\lambda \leq 10^4$. A detailed description of this instrument and its performance is given by Krämer et al. (1990) and Barnstedt et al. (1998).

Only one SMC target has been observed with the echelle during the *ORFEUS II* mission of Nov./Dec. 1996: HD 5980. It is the brightest stellar object in the SMC, variable, and known for further extraordinary properties, as shown by Moffat et al. (1998). With its brightness and high temperature, as well as due to its relatively low extinction of $E(B-V) = 0.07$ (Fitzpatrick & Savage 1983, hereafter FS83), HD 5980 provides us with a large UV flux and therefore is a good background source for the investigation of the SMC foregroud gas along this line of sight. HD 5980 was also observed by *HUT* (Schulte-Ladbeck et al. 1995) but with a spectral resolution insufficient to resolve H_2. The *IUE* spectrum of HD 5980 shows the main SMC absorption in radial velocity near +140 km s^{-1} and one additional component at +300 km s^{-1} (FS83). The *ORFEUS* spectrum, obtained when $V \simeq 10.8$ mag, shows both these components, in particular also in O VI (Widmann et al. 1998). McGee & Newton (1986) showed the existence of neutral hydrogen in 21-cm emission at +123 km s^{-1} and at +163 km s^{-1}. We therefore expected to see H_2 belonging to the neutral SMC gas near those velocities, although due to the low extinction towards HD 5980 the H_2 absorption might be too weak and below our detection limit.

As shown by its near-IR emission, H_2 exists in the SMC (Koornneef & Israel 1985) as well as in the LMC (Israel & Koornneef 1991a, 1991b). The present paper, together with the detection of H_2 absorption profiles in the LMC (de Boer et al. 1998), presents the first studies of interstellar H_2 in the Magellanic Clouds via high resolution FUV spectroscopy.

Send offprint requests to: prichter@astro.uni-bonn.de

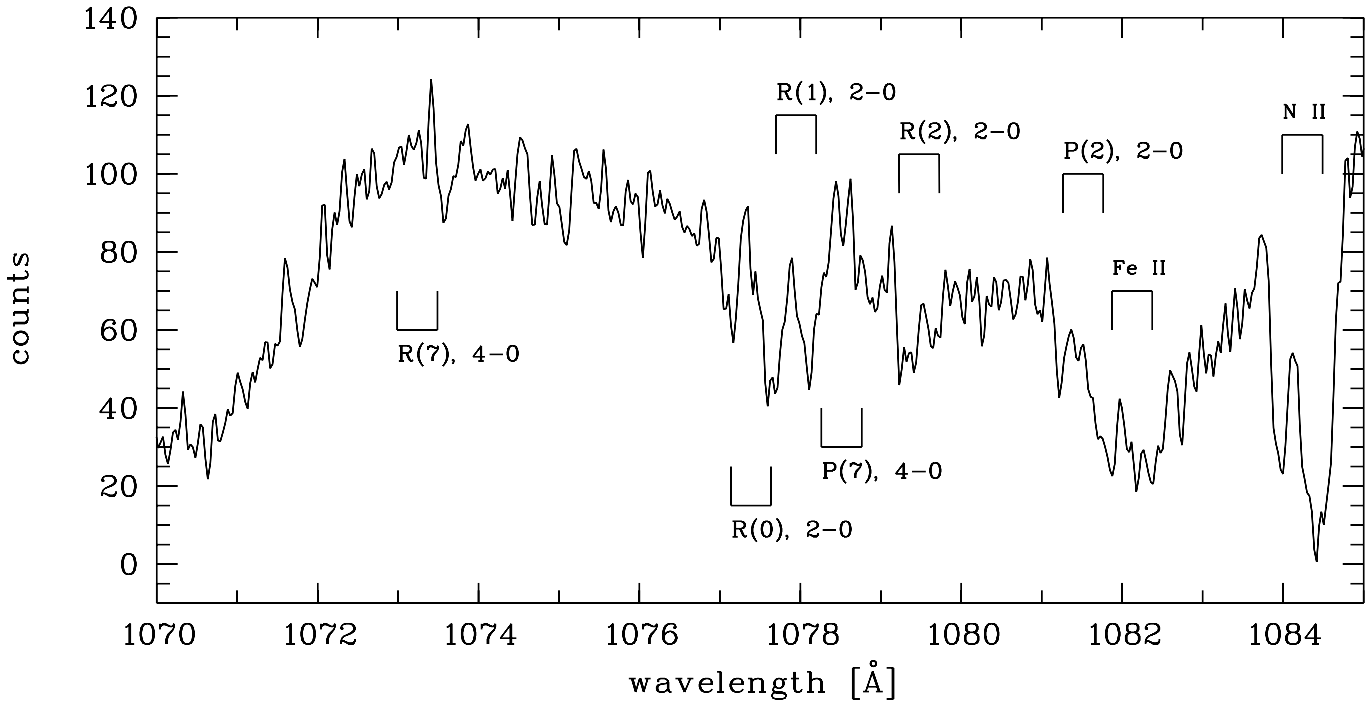

Fig. 1. The detected H_2 lines in the displayed wavelength range of the *ORFEUS* spectrum of HD 5980 are identified. The spectrum covers H_2 absorption from the ground states as well from rotational states as high as $J = 7$. The vertical marks indicate the expected wavelength positions for zero radial velocity (galactic gas) and for 150 km s^{-1} (SMC gas). The spectral resolution is $\simeq 30$ km s^{-1}

2. Observations and data reduction

HD 5980 has been observed on 1+2 Dec. with a total observing time of 4800 s. After the main data reduction (see Barnstedt et al. 1998 for details) the individual echelle orders have been filtered by a wavelet algorithm (Fligge & Solanki 1997). Our spectrum shows a signal-to-noise ratio (S/N) of $\simeq 25$ for wavelengths > 1000 Å; in the range < 1000 Å the lower sensitivity leads to a much poorer S/N. The range below 1000 Å is difficult to analyse, because the density of H_2 absorption lines is very high in that range. Nearly all H_2 lines are blended by other transitions and atomic lines and their components. In the spectral range between 1000 and 1130 Å we found 17 reasonably clean H_2 absorption lines with absorption at SMC velocities. A portion of the spectrum of HD 5980 is shown in Fig. 1.

Some of the identified H_2 lines are plotted in the velocity scale (LSR) in Fig. 2. We detect absorption features from the lowest 8 rotational states. Our detection limit is $W_\lambda \simeq 25$ mÅ. Inspecting Fig. 2 it is immediately clear that the H_2 lines of the low J levels have absorption near +120 km s^{-1} and those of high J levels near +160 km s^{-1}.

3. H_2 column densities for the SMC gas

The fact that we find H_2 absorption in the SMC at $\simeq$ +120 km s^{-1} and at $\simeq$ +160 km s^{-1}, while the atomic component is visible near +140 km s^{-1} is an indicator for the complexity of the SMC gas along this line of sight. A detailed analysis of the atomic lines in *IUE* spectra is given by FS83. For the further analysis of the H_2 absorption we call the SMC component at +120 km s^{-1} *Cloud A* and the one at +160 km s^{-1} *Cloud B*.

Table 1. H_2 column densities toward HD 5980

	Rotation level J	$\log N(J)$ [a] [cm^{-2}]	b-value [km s^{-1}]	Number of lines used
Cloud A	0	16.57	6	2
	1	15.90	6	4
	2	14.60	6	2
Cloud B	5	15.00	9	1
	6	14.39	9	2
	7	14.75	9	4

[a] for uncertainties see the error bars in Fig. 4

For $J = 0, 1, 2$ only *Cloud A* shows strong H_2 lines; a contribution by *Cloud B* might be present very weakly, but its absorption lies in the wings of the *Cloud A* and therefore is not visible. For $J = 3$ and 4 the *Cloud B* absorption becomes stronger and overlaps with the *Cloud A* component, so that with our spectral resolution of $\simeq 30$ km s^{-1} the H_2 lines from both components combine to one single wider absorption feature. At this stage of data analysis we do not attempt to separate the two clouds from each other in these intermediate J level lines.

To derive H_2 column densities for the SMC gas we have to construct curves of growth for each cloud individually. For that we use the f-values from Morton & Dinerstein (1976).

For *Cloud A* we fitted 8 H_2 lines of $J = 0, 1, 2$ to a curve of growth with a velocity dispersion of $b = 5$ km s^{-1}. The total column density for $J \leq 2$ is $N_A(H_2) = 4.6 \times 10^{16}$ cm^{-2}.

In *Cloud B* at +160 km s^{-1} we find H_2 absorption for the higher states $J = 5, 6, 7$ only. The existence of absorption from

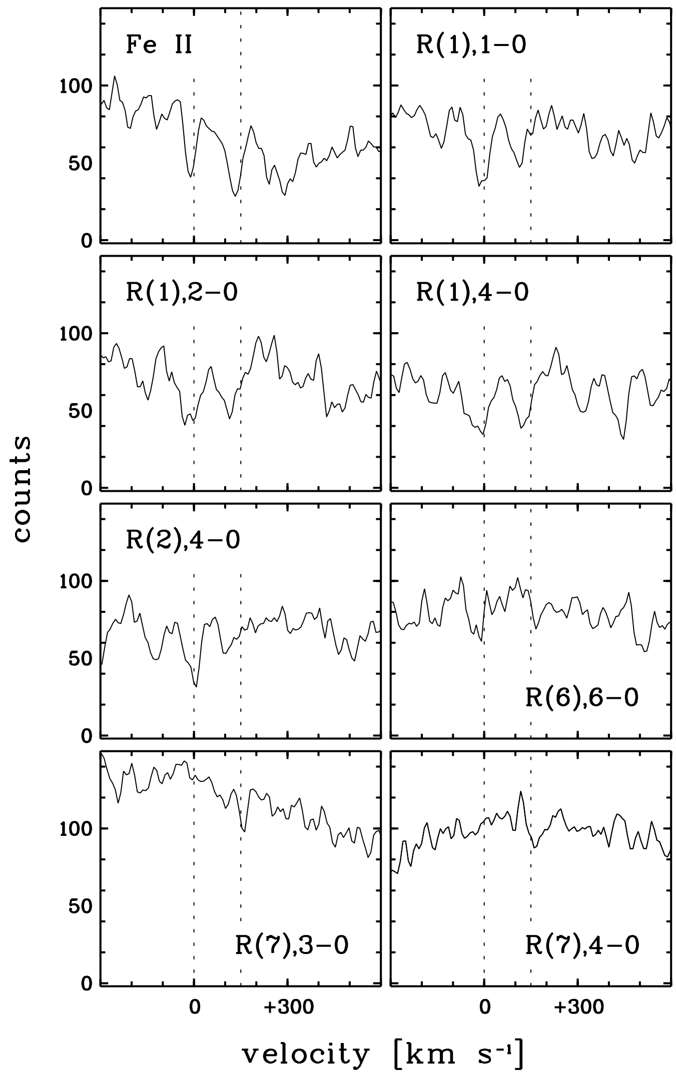

Fig. 2. A selection of H_2 lines has been plotted in the velocity scale. Galactic material absorbs at 0 km s^{-1}. The SMC H_2 component for the lower roational states ($J \leq 3$) is visible near +120 km s^{-1}, while the one for the higher states ($5 \leq J \leq 7$) is present at +160 km s^{-1}. The difference in the velocities indicates the presence of *two* SMC clouds in our line of sight. At the top the profile of Fe II at 1122.97 Å is presented showing absorption near +140 km s^{-1}. The dotted lines indicate the velocities at 0 km s^{-1} and 150 km s^{-1} (LSR)

such high states indicates that the gas in *Cloud B* is highly excited. The best fit for levels $J = 5, 6, 7$ is given by a curve of growth with $b = 9$ km s^{-1}.

Both fits to the curve of growth are shown in Fig. 3, the obtained column densities can be found in Table 1.

For *Cloud B* we estimate the total amount of H_2 by extrapolating the observed amount in the excited levels based on the equivalent excitation temperature (see Sect. 4). We so find $N_B(H_2) = 4.8 \times 10^{15}$ cm^{-2}. The 21-cm emission of the neutral hydrogen shows a strong component at +160 km s^{-1} (McGee & Newton 1986).

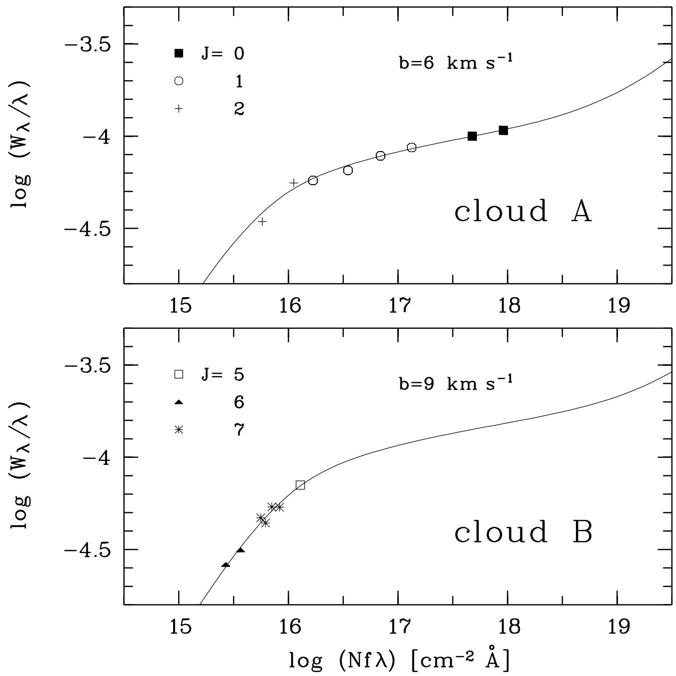

Fig. 3. The empirical curves of gowth for two SMC clouds are shown. *Cloud A* is at $\simeq$ +120 km s^{-1} and has no absorption from the higher rotational states, *Cloud B* is at $\simeq$ +160 km s^{-1} and has only marginal absorption from the lower J states

4. H_2 excitation state

Collisional excitation as well as the UV pumping are the processes responsible for the population of the molecules excited states (Spitzer & Zweibel 1974). A measure for the kinetic state of the the gas is the equivalent excitation temperature, which can be obained by fitting the given population density by a Boltzmann distribution, as shown in Fig. 4. The column densities $N(J)$ for both SMC clouds, devided by their statistical weigth g_J, are plotted against the excitation energy E_J.

For *Cloud A* we derive an equivalent excitation temperature of $\simeq$ 70 K. That means that the 3 lowest roational states of *Cloud A* are most likely collisionally excited, so that the derived temperature reflects the kinetic state of that gas.

The situation looks different for *Cloud B*, where the fit for $5 \leq J \leq 7$ leads to an equivalent excitation temperature of $\simeq$ 2350 K. This temperature is not the kinetic temperature of the gas, but gives the population of the excitation states due to very strong UV pumping, likely caused by the high UV photon flux environment of the SMC gas at +160 km s^{-1}.

5. Interpretation

5.1. Cloud A

The excitation temperature for *Cloud A* is similar to values found in many studies of H_2 gas in the Milky Way (Spitzer et al. 1974). If we assume a galactic foreground reddening of $E(B-V) = 0.02$ (McNamara & Feltz 1980), the reddening in the SMC gas is $E(B-V) = 0.05$ for this line of sight. The

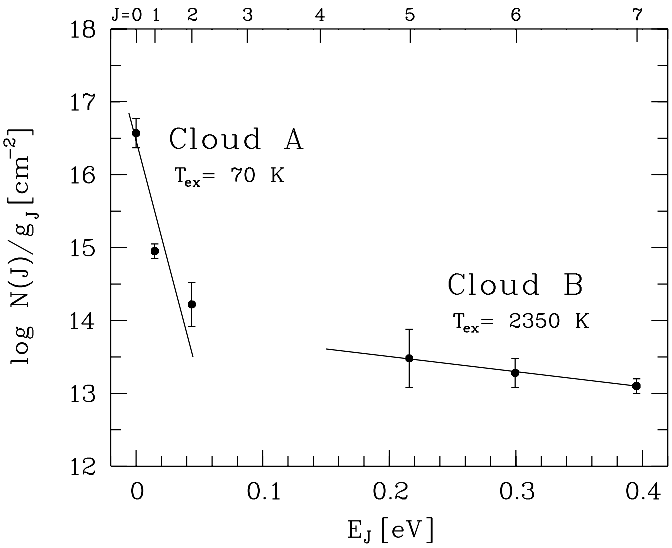

Fig. 4. The H_2 column densities, devided by their statistical weight, are plotted against the excitation energy. For *Cloud A* we obtain an equivalent excitation temperature of $\simeq$ 70 K for $J \leq 2$, for *Cloud B* the states $5 \leq J \leq 7$ fit to a temperature of $\simeq$ 2350 K. The derived temperatures are indicated by the solid lines. The errors shown are based on the uncertainties in the fits of the curves of growth

fact that we find absorption by H_2 in the SMC gas toward a star with that low extinction underlines that the gas-to-dust ratio in the interstellar gas in the SMC is significantly higher than the Galactic value (FS83). Neutral hydrogen has been detected in 21-cm emission towards HD 5980 at +123 km s^{-1} with a column density $N(\text{H I}) \simeq 1.39 \times 10^{21}$ cm^{-2} (McGee & Newton 1986). Since this velocity is the same as that of *Cloud A* and since *Cloud A* shows little UV pumping, it lies likely well in front of HD 5980. We thus can compare $N(\text{H}_2)$ andb $N(\text{H I})$ and derive $f = 2N(\text{H}_2)/[N(\text{H I}){+}2N(\text{H}_2)] = 6.6 \times 10^{-5}$ as the fraction of hydrogen nuclei in molecular form in the interstellar gas of this cloud. In view of the column density of $N(\text{H I})$ at this velocity we place this cloud in the foreground of the SMC.

5.2. *Cloud B*

The equivalent excitation temperature of $\simeq$ 2350 K for *Cloud B* is the highest one ever seen in studies of H_2 absorption and indicates a strong UV radiation field in gas in the direct environment of *Cloud B,* probably from the target HD 5980 itself. However, given the high excitation state and the large $N(\text{H I})$ from 21 cm at the same velocity, we suggest that the main H I emission comes from gas *behind* HD 5980 (see also FS83).

HD 5980 is the visually brightest hot luminous stellar member of the association NGC 346, exciting the large H II region N 66. The star was in the late 1980s of WNE+OB type with anomalously bright emission lines (Conti et al. 1989). HD 5980 is an eclipsing binary with a period of 19.3 days, composed of a WN star and an O star with interacting stellar winds. The star brightened slowly as of that time and the spectrum changed since then (see Moffat et al. 1998 for the details). During the ORFEUS measurements the star was of spectral type WN 7.

As shown in the *IUE* spectrum of HD 5980, absorption by C IV and Si IV occurs at velocities near +150 km s^{-1}. FS83 conclude that the bulk of this highly ionized gas is formed by stellar photoionization of HD 5980. Since we detect H_2 near +160 km s^{-1} in *Cloud B* it is reasonable to believe that the molecular gas belongs to the component found by FS83. The H_2 of *Cloud B* is highly influenced by the large UV flux of HD 5980 and of NGC 346 as a whole, and thus likely resides in the immediate surrounding of the star and the cluster.

6. Concluding remarks

The *ORFEUS* FUV spectrum of HD 5980 shows absorption by interstellar H_2 in the SMC. Two velocity components have been detected belonging to the SMC gas. H_2 gas at +120 km s^{-1} is predominantly collisionally excited, as indicated by the lowest three rotational states. It is similar to galactic H_2 gas. H_2 gas seen at +160 km s^{-1} is highly excited, probably due to UV pumping by the abundant UV photons from HD 5980 and NGC 346. These findings represent, together with the *ORFEUS* detection of H_2 in the LMC (de Boer et al. 1998), the first studies of H_2 in absorption in the Magellanic Clouds.

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