Letter to the Editor

ORFEUS II echelle spectra: Detection of H$_2$ absorption in SMC gas

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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 $\approx 70$ 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 $\approx 2350$ 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 emission 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 $\lambda/\Delta \lambda \approx 5 \cdot 10^3$ 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 foreground 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 $V \approx 10.8$ 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.
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 $\sim 25$ for wavelengths $>1000\,\text{Å}$; in the range $<1000\,\text{Å}$ the lower sensitivity leads to a much poorer S/N. The range below $1000\,\text{Å}$ 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 is clear that the H$_2$ lines of the low $J$ levels have absorption near $+120\,\text{km s}^{-1}$ and those of high $J$ levels near $+160\,\text{km s}^{-1}$.

3. H$_2$ column densities for the SMC gas

The fact that we find H$_2$ absorption in the SMC at $\sim +120\,\text{km s}^{-1}$ and at $\sim +160\,\text{km s}^{-1}$, while the atomic component is visible near $+140\,\text{km s}^{-1}$, 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 $+120\,\text{km s}^{-1}$ Cloud A and the one at $+160\,\text{km s}^{-1}$ Cloud B.

### Table 1. H$_2$ column densities toward HD 5980

| Rotation level $J$ | $\log N(J)$ [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 $\sim 30\,\text{km s}^{-1}$ 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 $b = 5\,\text{km s}^{-1}$. The total column density for $J \leq 2$ is $N_A(H_2) = 4.6 \times 10^{16}\,\text{cm}^{-2}$.

In Cloud B at $+160\,\text{km s}^{-1}$ we find H$_2$ absorption for the higher states $J = 5, 6, 7$ only. The existence of absorption from
A selection of $\text{H}_2$ lines has been plotted in the velocity scale. Galactic material absorbs at 0 km s$^{-1}$. The SMC $\text{H}_2$ component for the lower rotational 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 $\text{H}_2$ by extrapolating the observed amount in the excited levels based on the equivalent excitation temperature (see Sect. 4). We so find $N_B(\text{H}_2) = 4.8 \times 10^{15}$ cm$^{-2}$. The 21-cm emission of the neutral hydrogen shows a strong component at +160 km s$^{-1}$ (McGee & Newton 1986).

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 $\text{H}_2$ 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 equivalent excitation temperature of Cloud B at this velocity we place this cloud in the foreground of the SMC. In view of the column density of the fraction of hydrogen nuclei in molecular form 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 $N$(H\textsc{i}) $\simeq$ 1.39 x 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 $N$(H$_2$) and $N$(H\textsc{i}) and derive $f = 2N$(H$_2$)/[N(H\textsc{i})+2N(H$_2$)] = 6.6 x 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(H\textsc{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 $N$(H\textsc{i}) from 21 cm at the same velocity, we suggest that the main H\textsc{i} emission comes from gas in HD 5980 (see also FS83).

HD 5980 is the visually brightest hot luminous stellar member of the association NGC 346, exciting the large H\textsc{ii} region N66. 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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