Letter to the Editor

**ORFEUS II echelle spectra: Absorption by H\(_2\) in the LMC**

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**Abstract.** We report the first detection of H\(_2\) absorption profiles of LMC gas on the line of sight to star 3120 in the association LH 10 near the emission nebula N 11B. Transitions found in the Lyman band are used to derive a total column density \(N(H_2) = 6.6 \times 10^{18}\, \text{cm}^{-2}\). Excitation temperatures of \(\leq 50\, \text{K}\) for levels \(J \leq 1\) and of \(\approx 470\, \text{K}\) for levels \(2 \leq J \leq 4\) of H\(_2\) are derived. We conclude that moderate UV pumping influences the population even of the lowest rotational states in this LMC gas.

**Key words:** Space vehicles - ISM: molecules - Galaxies: ISM - Magellanic Clouds: LMC - Stars: individual: LH 10:3120 - Ultraviolet: ISM

1. Introduction

The last instrument capable of high resolution spectroscopy in the 900-1200 Å range was the *Copernicus* satellite (Spitzer et al. 1973), working in the 1970s. This part of the spectrum contains absorption transitions of the Lyman and Werner Bands of molecular hydrogen, H\(_2\), and of transitions of O VI and other species highly relevant for interstellar medium studies.

The *ORFEUS* (Krämer et al. 1990) and *IMAPS* (Jenkins et al. 1988) experiments on the *ASTRO-SPAS* space shuttle platform have provided access to the far UV spectral range in great detail. The *ORFEUS* telescope feeds two spectrographs. The Heidelberg-Tübingen echelle gives spectra from 912 to 1410 Å with \(\lambda/\Delta\lambda \leq 10^4\) which are recorded with a microchannel plate detector. Good S/N is achieved in exposure times of the order of 1 hr of hot objects with \(V < 12\, \text{mag}\) (Krämer et al. 1990). The UCB spectrograph produces spectra over the range of 390 to 1220 Å (Hurwitz et al. 1998) with a resolution too low for detailed interstellar work. *IMAPS* has its own telescope, works at \(\lambda/\Delta\lambda \sim 1.5 \times 10^5\) between 970 and 1195 Å, and is in overall sensitivity limited to galactic studies (see e.g. Jenkins & Peimbert 1997).

Here we report on the detection at high spectral resolution of H\(_2\) in the spectrum of the LMC star LH 10:3120. The star, located in the association LH 10 near the western edge of the LMC, is of spectral type O5.5Vf, has \(V = 12.80\, \text{mag}\) and \(E(B-V) = 0.17\, \text{mag}\) (Parker et al. 1992). The star was selected because of its very early spectral type, modest extinction (too large extinction would make the far-UV undetectable), and its proximity to an area where the molecule CO has been found in emission (Cohen et al. 1988; Israel et al. 1993).

The presence of H\(_2\) in the LMC is known since Israel & Koornneef (1988) detected the near-IR emission lines from radiatively excited H\(_2\) seen toward H II regions near hot stars. Measurements showed that H\(_2\) is abundantly available, both in the SMC (Koornneef & Israel 1985) and in the LMC (Israel & Koornneef 1991a, 1991b). Clayton et al. (1996) detected with *HUT* at 3 Å resolution broad depressions in the far-UV spectrum of two LMC stars, which could be fitted with H\(_2\) absorptions due to \(N(H_2) \approx 1-2 \times 10^{20}\, \text{cm}^{-2}\). Studies of H\(_2\) in the LMC and SMC are of importance because of the lower metal content of these galaxies compared to the Milky Way and the different gas to dust ratios (see Koornneef 1984).

2. Observations, data handling

The total observing time for LH 10:3120 in the *ORFEUS* space shuttle mission of Nov./Dec. 1996 was 6000 s in 3 pointings exploiting the integrating capabilities of the microchannel plate detector system. A detailed instrument description and information about the basic data reduction is given by Barnstedt et al. (1998). The data reduction for the 20 echelle orders has been performed by the *ORFEUS* team in Tübingen. The spectrum has been filtered by us with a de-noising algorithm basing on a wavelet transformation (Fligge & Solanki 1997). This leads to a slight degradation of the spectral resolution, now being equivalent to \(\approx 30\, \text{km s}^{-1}\). The spectra have a signal-to-noise (S/N) of \(\approx 20\) at the longer wavelengths of the recorded spectral range. Toward the shorter end of the spectral range, both the...

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* Data obtained under the DARA guest observing program in the *ORFEUS II* Mission
**Table 1.** \( \text{H}_2 \) column densities in LMC gas toward LH 10:3120

| Rotation level \( J \) | \( \log N(J) \) \( \left[ \text{cm}^{-2} \right] \) | \( b \)-value \( \left[ \text{km s}^{-1} \right] \) | Number of lines used |
|------------------------|------------------|-----------------|------------------|
| 0                      | 18.65            | 5               | 2                |
| 1                      | 18.10            | 5               | 5                |
| 2                      | 17.70            | 5               | 3                |
| 3                      | 17.50            | 5               | 3                |
| 4                      | 16.70            | 5               | 3                |

The increased effect of the UV-extinction as well as the wavelength dependent sensitivity of the instrument leads to a reduction in S/N such, that little can be done with the spectrum at \( \lambda < 1000 \) Å. After the filtering absorption features in the longer part of the spectrum become clearly visible.

We first inspected spectral ranges almost devoid of atomic absorption lines and where only few \( \text{H}_2 \) absorptions are expected. The reason for this is to avoid getting confused in the search for \( \text{H}_2 \) by the complexity of the absorption line profiles on the line of sight to the LMC. Yet, the characteristic pattern of absorption by the Milky Way disk near 0 km s\(^{-1}\), by the LMC near +270 km s\(^{-1}\), and possibly by high-velocity clouds near +60 and +130 km s\(^{-1}\) all known from \( \text{IUE} \) (see Savage & de Boer 1979, 1981; de Boer et al. 1980) and \( \text{HST} \) (Bomans et al. 1995) spectra, helps to identify the absorption structures.

A section of the echelle order 51, where several \( \text{H}_2 \) absorption lines have been found, is shown in Fig. 1. Many of the \( \text{H}_2 \) profiles overlap in their \( \sim 300 \) km s\(^{-1}\) wide profile structure and decompositions are not always possible. However, in some cases the galactic absorption stayed unblended, in other cases the LMC portion was blend free. For this first analysis we took 16 \( \text{H}_2 \) absorption lines from the lowest 5 rotational states for the further analysis. These lines are essentially free from any blending problems so that wrong identifications can be excluded. Absorption strengths could thus be determined for the LMC components seen in these absorption profiles. A selection of characteristic \( \text{H}_2 \) absorption line profiles in velocity scale (LSR) is shown in Fig. 2.

**3. \( \text{H}_2 \) column density in the LMC gas**

The absorption profiles have been analysed and decomposed into the various velocity components. Here we limit ourselves to the absorption pertaining to the LMC. For each line the absorption equivalent width has been determined. The \( f \)-values for the further analysis have been taken from Morton & Dinerstein (1976) for the \( \text{H}_2 \) transitions and for the atomic absorption lines from the compilation of Morton (1991). Theoretical Voigt profiles were fitted to some of the identified \( \text{H}_2 \) absorption lines and we thus could derive an upper limit for the velocity dispersion of \( b < 10 \) km s\(^{-1}\) for the LMC gas.

Subsequently, curves of growth have been constructed for each of the absorptions by the 5 rotational states for the LMC component. The logarithmic equivalent widths for each rotational level \( J \) have been shifted horizontally to give a fit to a theoretical single cloud curve of growth as a function of log \( N(J)/\lambda \). The best fit for all 5 rotational states was obtained with \( b = 5 \) km s\(^{-1}\) as shown in the empirical curve of growth for all identified \( \text{H}_2 \) lines (Fig. 3). The column densities \( N(J) \) derived in this way have been collected in Table 1. The uncertainties in the column densities are based on the quality of the
K.S. de Boer et al., ORFEUS observed H$_2$ absorption in LMC

Fig. 2. Examples of absorption profiles clearly showing the detection of H$_2$. At the top we present a profile of the Si II 1190.416 Å line for easy reference. The H$_2$ absorption is due to the Milky Way component near 0 km s$^{-1}$ and the LMC component near +270 km s$^{-1}$. The atomic line of Si II also shows the presence of the galactic halo high-velocity clouds near +60 and +130 km s$^{-1}$ (LSR).

Fig. 3. The H$_2$ lines were fitted to a single cloud curve of growth, indicating $b \approx 5$ km s$^{-1}$. The column densities for the levels $J = 0$ to 4 are given in Table 1.

Fig. 4. The column densities for the levels $J = 0$ to 4 of H$_2$ are plotted against the excitation energy. The higher levels exhibit an equivalent excitation temperature of $\approx 470$ K, the excitation being mostly due to UV pumping. For the two lowest levels the kinetic excitation temperature is $\leq 50$ K; the fit drawn marks the indicated upper limit.

4. Interpretation

4.1. Excitation state

To explain the column densities and the relative population of the rotational states of the H$_2$ molecule we have to determine the mechanism which is responsible for the excitation of the molecular gas on our line of sight. Two processes dominate the population of the excited states, collisional excitation and pumping by UV photons (Spitzer & Zweibel 1974). With the column densities for the individual rotational states we were able to determine the excitation temperature for the LMC gas for $J \leq 4$. In Fig. 4 the LMC column densities $N(J)$ divided by their statistical weight $g_J$ are plotted against the excitation energy $E_J$. The equivalent excitation temperature of the gas can be derived by fitting theoretical population densities from a Boltzmann distribution. For $J \geq 2$ we derive an equivalent excitation temperature of 470 K.

The plot of Fig. 4 shows also that the level $J = 0$ lies above the linear relation of 470 K. Thus at least the $J = 0$ level is populated through kinetic excitation. Fitting the Boltzmann relation to the $J = 0$ and 1 column densities we find a kinetic temperature of 50 K. Clearly, the population of level $J = 0$ is due to gas with a temperature $\leq 50$ K. Such very low gas tem-
The total column density found in the LMC can be related to the remainder of the cold molecular cloud which formed N 11B. It is tempting to relate the H 2 gas absorption with the UV pumping but not in an excessive way. The excitation level of the higher J levels on the line of sight to LH 10:3120 is equivalent to ≳470 K. Such values are also found for the higher rotational states in galactic gas (Snow 1977; Spitzer et al. 1974). The environment of N 11B has contributed to the UV pumping but not in an excessive way. The excitation of the lowest level indicates the gas is kinetically cold.

5. Concluding remarks

Our investigation of the ORFEUS far UV spectrum shows for the first time well resolved absorption profiles due to H 2 in LMC gas. The derived column densities and excitation temperatures toward LH 10:3120 demonstrate that UV pumping also takes place in LMC gas. The detected H 2 has a column density and an excitation state similar to that of Milky Way gas, even though the line of sight runs through an energetic environment. In closing we note that H 2 has also been detected in absorption by ORFEUS in the SMC (Richter et al. 1998).

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