The relation between column densities of interstellar OH and CH molecules

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ABSTRACT

We present a new, close relation between column densities of OH and CH molecules based on 16 translucent sightlines (six of them new) and confirm the theoretical oscillator strengths of the OH A–X transitions at 3078 and 3082 Å (0.001 05, 0.000 648) and CH B–X transitions at 3886 and 3890 Å (0.003 20, 0.002 10), respectively. We also report no difference between observed and previously modelled abundances of the OH molecule.

Key words: ISM: molecules.

1 INTRODUCTION

The interstellar OH molecule was discovered using the Λ doublet transition observed between the levels of the ground rotational state $^2\Pi_{3/2}$ $J = 3/2$ at 18 cm (Weinreb et al. 1963). Its two lines resulting from electronic transitions of the $A^2\Sigma^+$–$X^2\Pi_i$ band (near 3078 and 3082 Å), are available to ground-based observatories and were identified in ultraviolet spectra of 14 bright OB stars (Crutcher & Watson 1976; Chaffee & Lutz 1977; Felenbok & Roueff 1996; Spaans et al. 1998; Boissé et al. 2005; Weselak et al. 2009b, hereafter W2009b). These findings also allowed determinations of OH column densities along translucent sightlines. Earlier observations of the A–X band of the OH molecule have been reanalysed by Roueff (1996) applying new oscillator strengths to OH A–X transitions of the previously published line strengths. Interstellar lines of the CH molecule have been discovered by the Mount Wilson observers and identified by McKellar (1940a,b) in the spectra of OB stars due to its A–X feature centred near 4300 Å being the strongest observed interstellar line in the violet region easily accessible to photographic observations. However, this line is frequently saturated. Since the B–X system near 3886 Å is also quite frequently observed and much weaker than the A–X one, it is almost always unsaturated. Abundances of the CH molecule were proved to be very tightly correlated with those of the H_2 molecule (e.g. Mattila 1986; Weselak et al. 2004). The oscillator strengths of CH transitions were extensively analysed by Lien (1984). Models of diffuse and translucent clouds have been extensively discussed by van Dishoeck & Black (1986).

Here we extend the above-mentioned sample (W2009b) of the UV OH absorption bands adding ground-based observations, done using the high-resolution UVES spectrograph towards six new tar-

gets (HDs: 110432, 152236, 152249, 154445, 161056 and 170740). The aim of this work is to investigate relations between column densities of the OH and CH molecules and test oscillator strengths of OH A–X and CH B–X transitions based on unsaturated lines at 3078 and 3082 Å and 3886 and 3890 Å, respectively. To test oscillator strengths of the CH B–X transition, we also compare results from different instruments.

2 THE OBSERVATIONAL DATA

Most of our observational material, presented in Table 1, was obtained using the UVES spectrograph at European Southern Observatory (ESO) Paranal in Chile (u and v) with the resolution $R = 80\,000$; one object (HD 110432) was observed in the latest observing run (v). In the latest observing run, we also observed HDs 149757 and 151932 that are not given in Table 1. In cases of objects where we found no UVES spectra, we took the OH band intensities from the literature and the intensities of CH B–X molecular features from our own observations done using four other spectrographs. Spectra of four objects were acquired using the fibre-fed echelle spectrograph ($R = 30\,000$, $45\,000$ and $90\,000$) installed at the 1.8-m telescope of the Bohyunsan Optical Astronomy Observatory (BOAO) in South Korea (b). Spectra of two objects was obtained using HARPS spectrometer (h), fed with the 3.6-m ESO telescope at La Silla ($R = 115\,000$). Three objects were observed using FEROS spectrograph (f) ($R = 48\,000$) fed by the 2.2-m ESO telescope at La Silla and two with MAESTRO fed by the 2-m telescope of the Observatory at Peak Terskol (t) ($R = 80\,000$). The spectrum of HD 34078 was also obtained with GECKO spectrograph (g), fed with the 3.6-m Canada–France–Hawaii Telescope (CFHT) (the spectral resolution is 120 000). Each of the above-mentioned instruments is described in the publications of Weselak et al. (2008a) and W2009b.

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Table 1. Measured equivalent widths of interstellar features and calculated column densities of the OH and CH molecules towards six new targets in the case of which the OH transitions at 3078 and 3082 Å were detected. Instruments are designated as follows: f-FEROS, u, v-UVES.

HD	Obs	Spec/L	EBV	OH W(3078) (mÅ)	OH W(3082) (mÅ)	CH W(3886) (mÅ)	CH W(3890) (mÅ)	N(OH) (10^{12} cm^{-2})	N(CH–BX) (10^{12} cm^{-2})	N(CH) (10^{12} cm^{-2})	N(H$_2$) (10^{20} cm^{-2})
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
110432	f	B2pe	0.48	1.81 ± 0.41	1.28 ± 0.34	4.10 ± 0.20	2.40 ± 0.20	39.72 ± 6.22	18.12 ± 0.28	17.91 ± 0.61	4.37[a]
	v					3.88 ± 0.20	2.43 ± 0.30		17.71 ± 0.36		
152236	u	B1Iape	0.66	3.50 ± 0.44	2.41 ± 0.34	5.34 ± 0.45	4.15 ± 0.56	75.62 ± 4.30	27.24 ± 0.72	27.05 ± 3.10	5.37[b]
	f					5.10 ± 0.80	4.20 ± 0.60		26.86 ± 1.00		
152249	u	O9Ib	0.48	2.81 ± 1.00	1.82 ± 0.80	3.40 ± 0.50	2.61 ± 0.40	58.61 ± 14.64	17.23 ± 1.39	17.23 ± 1.39	
154445	u	B1V	0.35	2.01 ± 0.31	1.52 ± 0.33	4.06 ± 0.20	2.84 ± 0.20	45.92 ± 10.98	19.59 ± 0.39	19.59 ± 0.39	
161056	u	B1V	0.60	8.38 ± 0.77	5.30 ± 0.67	12.70 ± 0.50	8.80 ± 0.40	172.46 ± 12.31	60.98 ± 1.39	60.98 ± 1.39	
170740	u	B2V	0.45	1.97 ± 0.43	1.73 ± 0.31	5.10 ± 0.29	2.84 ± 0.20	47.29 ± 9.15	22.02 ± 0.57	22.02 ± 0.57	7.24[a]

Note. In columns (9)–(11), we present column density of the OH molecule based on the A–X transition, column density of the CH molecule based on the B–X transition and total column density of the CH molecule averaged in the case of multiple results, respectively (see also text). In column (12), we present data on column densities of H$_2$ with [a]Rachford et al. (2002), [b]Rachford et al. (2009). Data on H$_2$ towards other targets are presented in the publication of W2009b.

All the spectra were reduced using the standard packages MIDAS and IRAF, as well as our own DECH code (Galazutdinov 1992), which provides all the standard procedures of image and spectra processing. In each case the continuum placement and equivalent width measurement, based on a Gaussian fit, were performed as in the publication of Weselak et al. (2009a). Due to the very low density of interstellar clouds, the only efficient line broadening mechanism can be the Doppler one.

3 RESULTS AND DISCUSSION

To obtain column densities, we used the relation of Herbig (1968) which gives proper column densities when the observed lines are unsaturated:

$$N = 1.13 \times 10^{20} W_\lambda / (\lambda^2 f), \qquad (1)$$

where W_λ and λ are in Å and column density in cm^{-2}. To obtain column density, we adopted f-values based on the publications of Roueff (1996) in the case of the A–X transition of the OH molecule and Lien (1984) in the case of the B–X transition of the CH molecule (W2009b). The resulting column densities of each molecule towards the target stars are given in Table 1. In the case of OH and CH molecules, the resulting column density was obtained as a sum of column densities originating in each line of OH and CH, respectively. In the case of the CH B–X band, which was observed by several instruments, the resultant column densities of the CH molecule were averaged.[1] We also found new column densities of

the OH molecule towards our target stars.[2] As already mentioned, we used the unsaturated bands of the selected molecules.

We examined the intensity ratio of the OH features at 3078 and 3082 Å based on 16 sightlines. Since their wavelengths are very close, the strength ratio should be very similar to that of their oscillator strengths. The latter, according to Felenbok and Roueff (1996), are equal to 1.05(−3) and 6.48(−4), respectively. Our new result (1.62 ± 0.03 with a correlation coefficient of 0.99) demonstrates that the equivalent width ratio matches exactly that of the oscillator strengths, thus confirming that our measurements are precise. We also tested the relation between equivalent widths of unsaturated 3886 and 3890 Å lines of CH as measured in spectra from six different instruments. Our fit to data points (1.43 ± 0.05 with a correlation coefficient of 0.99) is consistent with the theoretical intensity ratio based on the oscillator strengths published by Lien (1984). This suggests that the intensity ratio of unsaturated 3886 and 3890 Å lines of CH is close to the expected theoretical value (1.50) suggested by Lien (1984).

We also found a new relation between column densities of the OH and CH molecules based on our observations. A new fit to data points based on our 16 results [N(OH) = 2.86 ± 0.12 N(CH) − 11.41 ± 4.73 (in 10^{12} cm^{-2})] with correlation coefficient equal to 0.99 is close to previous relation presented by W2009b, i.e. [N(OH) = 2.62 ± 0.17 N(CH) − 6.75 ± 7.85 (in 10^{12} cm^{-2})] based on 10 data points.

In Table 2, we compare column density ratios presented by Liszt & Lucas (2002) with average ratios calculated on the basis results presented in this work. It is well seen that OH/CH, OH/H$_2$ and CH/H$_2$ ratios are close to those published previously. Our results on NH/H$_2$ and OH/NH are based on column densities of the NH molecule presented in the publication of Weselak et al. (2009c) and

[1]Column densities (in 10^{12} cm^{-2}) of the CH molecule in the case of multiple results in the case of HD 23180 (t): 20.84 ± 0.36 [based on W(3886) = 4.20 ± 0.30 and W(3890) = 3.10 ± 0.20] was averaged with that published by W2009b to obtain the final column density equal to 21.54 ± 1.70; HD 24398 (t): 20.48 ± 0.71 [based on W(3886) = 4.50 ± 0.50 and W(3890) = 2.80 ± 0.50] was averaged with that published by W2009b to obtain 21.39 ± 2.06; HD 34078 (b): 84.27 ± 1.92 [based on W(3886) = 18.10 ± 1.50 and W(3890) = 11.80 ± 1.20] was averaged with that published by W2009b to obtain 81.77 ± 8.31; HD 149757 (v and f): 25.29 ± 0.28 and 25.13 ± 0.71 [based on W(3886) = 5.48 ± 0.20 and 5.50 ± 0.50 and W(3890) = 3.51 ± 0.20 and 3.45 ± 0.50] was averaged with that published by W2009b to obtain 25.29 ± 1.61; HD 151932 (v): 27.70 ± 1.02 [based on W(3886) = 5.75 ± 0.41 and W(3890) = 4.01 ± 0.32]; HD 163800 (u): 33.81 ± 0.50 [based on W(3886) = 7.10 ± 0.30 and W(3890) = 4.84 ± 0.40] was averaged with that published by W2009b to obtain 34.08 ± 1.23.

[2]Column densities (in 10^{12} cm^{-2}) of the OH molecule in the case of HD 147889 (u): 268.68 ± 30.74 [based on W(3078) = 13.80 ± 1.74 and W(3082) = 7.89 ± 1.68]; HD 148688 (u): 24.73 ± 9.88 [based on W(3078) = 1.10 ± 0.45 and W(3082) = 0.81 ± 0.54]; HD 149757 (v): 43.62 ± 6.04 [based on W(3078) = 2.10 ± 0.67 and W(3082) = 1.35 ± 0.32]; HD 151932 (v): 71.49 ± 10.25 [based on W(3078) = 3.61 ± 0.42 and W(3082) = 2.13 ± 0.26]; HD 152270 (u): 45.01 ± 12.81 [based on W(3078) = 1.95 ± 0.64 and W(3082) = 1.50 ± 0.70]; HD 163800 (u): 78.43 ± 14.27 [based on W(3078) = 3.69 ± 0.82 and W(3082) = 2.31 ± 0.78]; HD 169454 (u): 101.01 ± 13.17 [based on W(3078) = 5.14 ± 0.85 and W(3082) = 2.99 ± 0.72].

Table 2. Column density ratios of diatomic molecules presented by Liszt & Lucas (2002) compared with averaged values obtained in this work. Column densities of NH were taken from Weselak et al. (2009c) and those of H_2 were taken from W2009b. Our new results are based on (1): 16, (2): 5, (3): 4 objects.

Molecular column density ratio	Liszt & Lucas (2002)	This work	
OH/CH	3.0 ± 0.9	2.52 ± 0.35	(1)
OH/H_2	$1.0 \pm 0.2 \times 10^{-7}$	$1.05 \pm 0.14 \times 10^{-7}$	(2)
CH/H_2	$4.3 \pm 1.9 \times 10^{-8}$	$4.32 \pm 0.52 \times 10^{-8}$	(2)
NH/H_2	$1.9 \pm 0.1 \times 10^{-9}$	$4.30 \pm 1.12 \times 10^{-9}$	(3)
OH/NH	50.2 ± 5.1	27.78 ± 7.47	(3)

Table 3. Comparison of our results on column densities (in 10^{12} cm^{-2}) of neutral diatomic molecules containing hydrogen (Obs.) with those calculated by van Dishoeck & Black 1986 (letter denotes model; in the case of HD 148184 averages calculated from various models). We designate observational data from (a) Roueff (1996), (b) Felenbok and Roueff (1996), (c) this work, (d) Weselak et al. (2008b), (e) Meyer & Roth (1991) and (f) Weselak et al. (2009c).

	HD 23180		HD 24398		HD 148184		HD 149757	
	Obs.	F	Obs.	F	Obs.	A–G	Obs.	A
OH	78 ± 26^a	75	40.5 ± 4^b	48	–	40	43.6 ± 6.0^c	43
CH	21.5 ± 1.7^c	12	21.4 ± 2.1^c	17	35.3 ± 0.2^d	12	25.3 ± 1.6^c	20
NH	–	0.77	0.90^e	0.33	–	0.37	0.76 ± 0.25^f	0.40

data on H_2 taken from the literature. In the case of relations with column densities of the NH molecule, our results differ from those presented by Liszt & Lucas (2002); the column densities of the NH molecule are not correlated with other species containing hydrogen (Weselak et al. 2009c).

In Table 3, we also compare observational results on column densities of neutral diatomic molecules containing hydrogen (i.e. OH, CH and NH) with results based on calculations of van Dishoeck & Black (1986) towards four stars: HD 23180, 24398, 148184 and 149757. Small differences between calculated and observed column densities exist in the case of the OH molecule (HD 23180 model F, 24398 model F, 149757 model A). These models were selected on the basis of small differences between calculated and observed column densities of the OH and CH molecules that were very well correlated (W2009b). No data on column densities of the OH and NH molecules are reported towards HD 148184. In this case, we compared the column density of the CH molecule taken from the publication of Weselak et al. (2008b) with the average calculated from models A–G of van Dishoeck & Black (1986). In Table 3, we present differences between calculated and observed values of the column density of the NH molecule. These differences were previously extensively discussed by Meyer & Roth (1991). The abundance of NH towards HD 24398 was calculated by Wagenblast et al. (1993). In this model which includes the formation of NH and OH on grains [with $(n_H)_0 = 100$ cm^{-3}, $T_0 = 30$ K and $I_{UV} = 0.08$], abundances of OH, CH and NH molecules are 42, 21 and 0.82 × 10^{12} cm^{-2}, compared to observational results (from Table 3) equal to 40.5 ± 4, 21.4 ± 2.1 and 0.90×10^{12} cm^{-2}, respectively. The comparison of calculated and observed column densities strongly supports the fact that NH and OH molecules are formed in the way of dust chemistry.

Table 4 presents physical conditions towards HD 23180, 24398 and 149757 based on comparison of our observational results with those calculated by van Dishoeck & Black (1986) – see also Table 3. We stress that it is only in the case of the OH molecule that no difference exists between calculated and observed column densities.

Table 4. Physical conditions in diffuse clouds towards HDs 23180, 24398 and 149757 based on comparison of observational (this work) and calculated (van Dishoeck & Black 1986) column densities of the OH and CH molecules (selected models in Table 3). In each case, we present the number of hydrogen atoms (in cm^{-3}), the temperature (in K) and the radiation field in the cloud core.

Parameter model	HD 23180 F	HD 24398 F	HD 149757 A
$(n_H)_0$ (cm^{-3})	250	325	600
T_0 (K)	20	30	30
I_{UV}	4.0	3.5	4.0

4 CONCLUSIONS

The above considerations led us to infer the following conclusions.

(i) We confirm oscillator strengths of the OH A–X transitions at 3078 and 3082 Å (0.001 05, 0.000 648) and CH B–X transitions at 3886 and 3890 Å, (0.003 20, 0.002 10).

(ii) We report no difference between observed and calculated column densities of the OH molecule towards HD 23180, 24398 and 149757 (based on selected models of van Dishoeck & Black 1986).

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