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The relation between interstellar OH and other simple molecules

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ABSTRACT

We discuss the close relation between the column densities of interstellar OH and CH molecules. Our results are obtained on the basis of 10 new sightlines. The OH molecule seems not to be spatially correlated with either CH^+ or CN simple species.

Key words. ISM: molecules

Introduction

The 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); later its electronic transitions were identified in ultraviolet spectra of 6 bright OB-stars HDs: 149757, 23180, 24398, 27778, 154368 and 34078 (Crutcher & Watson 1976; Chaffee & Lutz 1977; Felenbok & Roueff 1996; Spaans et al. 1998; Boissé et al. 2005). Two lines of the $A^2\Sigma^+ - X^2\Pi_i$ band near 3078 and 3082 Å are available to ground-based observatories whereas those of $D^2\Sigma^- - X^2\Pi_i$, near 1222 Å are available only to space-born instruments; the latter have been reported based on Copernicus OAO−3 observations (Snow 1976). These findings allowed determinations of OH column densities toward the abovementioned targets. They have been reanalyzed by Roueff (1996) applying new oscillator strengths to both OH A−X and D−X transitions of the previously published line strengths.

Here we extend the abovementioned sample of UV OH absorption bands adding ground-based observations, done using the high-resolution UVES spectrograph toward 10 new targets. The aim of this work is to investigate relations between column densities of the OH molecule and those of simple diatomic molecules such as CH, CH^+ and CN, identified in the interstellar medium (ISM) by McKellar (1940a,b). The CH molecule is closely related to molecular hydrogen (H_2, as already shown by Mattila 1986; Weselak et al. 2004). On the other hand, column densities of the CH cation and H_2 show large scatter suggesting the lack of a relation between these two molecules (Weselak et al. 2008a). Abundance ratios of simple molecular species may efficiently constrain proposed paths of chemical reactions which likely take place in interstellar clouds.

Weselak et al. (2008b) showed that CH molecule seems to be quite tightly correlated with narrow diffuse interstellar bands (DIBs). Abundance relations between simple molecular species may constrain the identification of DIB carriers – very likely complex molecules. The scarcity of the currently available samples makes this task very difficult. An extension of both samples, of the considered molecular species and of the observed targets, seems thus of real importance.

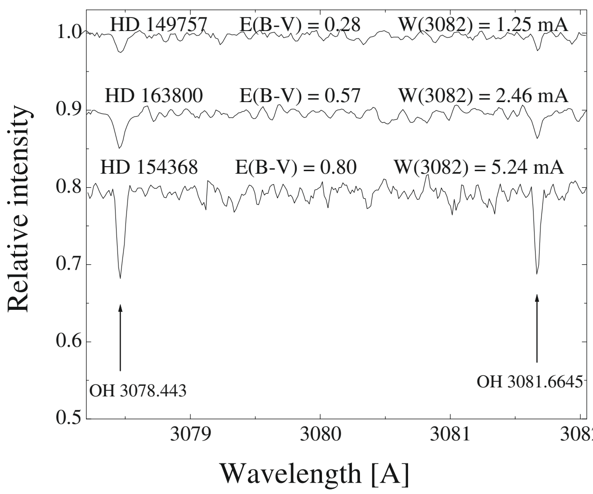

Fig. 1. The OH molecule A−X system centered near 3078 and 3082 Å seen in spectra of 3 objects characterized with different $E(B-V)$. Note the increasing equivalent widths of both 3078 and 3082 lines with the interstellar reddening.

The observational data

In Table 1 we present identifications of all transitions in all molecular species considered in this paper. Figure 1 presents the spectral region of electronic OH transitions at 3078 and 3082 Å in spectra of 3 stars observed using UVES. Generally, intensities of both features grow with $E(B-V)$, suggesting that column densities of OH and of dust grains are mutually correlated. In

Table 1. Adopted molecular parameters.

Species	Vibronic band	Rotational lines	Position [Å]	Ref.	f-value	Ref.
OH	$A^2\Sigma^+$–$X^2\Pi_i$ (0, 0)	$Q_1(3/2)+{}^QP_{21}(3/2)$	3078.443	1	0.00105	2
	(0, 0)	$P_1(3/2)$	3081.6645	1	0.000648	2
CH	$B^2\Sigma^-$–$X^2\Pi$ (0, 0)	$Q_2(1)+{}^QR_{12}(1)$	3886.409	3	0.00320	3
	(0, 0)	${}^PQ_{12}(1)$	3890.217	3	0.00210	3
CH^+	$A^1\Pi$–$X^1\Sigma^+$ (0, 0)	R(0)	4232.548	3	0.00545	3
	(1, 0)	R(0)	3957.689	4	0.00342	4
	(2, 0)	R(0)	3745.308	4	0.00172	4
CN	$B^2\Sigma^+$–$X^2\Sigma^+$ (1, 0)	R(0)	3579.963	5	0.00300	5
	(1, 0)	R(1)	3579.453	5	0.00200	5
	$B^2\Sigma^+$ – $X^2\Sigma^+$ (0, 0)	R(0)	3874.608	5	0.03420	5
	(0, 0)	R(1)	3873.998	5	0.02280	5
	$A^2\Pi$–$X^2\Sigma^+$ (1, 0)	$R_1(0)$	9186.935	6	0.000792	6
	(1, 0)	$R_1(1)$	9183.216	6	0.000501	6

References: 1 – this work; 2 – Felenbok & Roueff (1996); 3 – Gredel et al. (1993); 4 – Weselak et al. (2009a); 5 – Meyer et al. (1989); 6 – van Dishoeck & Black (1989).

Table 2. Measured equivalent widths of interstellar features.

HD/Obs	Sp/L	$E(B-V)$	OH $W(3078)$ [mÅ]	OH $W(3082)$ [mÅ]	CH $W(3886)$ [mÅ]	CH $W(3890)$ [mÅ]	CH^+ $W(3957)$ [mÅ]	CH^+ $W(4232)$ [mÅ]	CN W(R1) [mÅ]	CN W(R0) [mÅ]
23180 B	B1III	0.27	3.50 ± 1.10[a]		4.51 ± 0.56	3.29 ± 0.45	4.30 ± 0.30	5.80 ± 0.28	1.92 ± 0.30	5.40 ± 0.33
24398 B	B1Iab	0.29	1.67 ± 0.08[b]	1.11 ± 0.05[b]	4.96 ± 0.50	3.01 ± 0.38	1.92 ± 0.87	3.90 ± 0.50	3.43 ± 0.54	9.01 ± 0.50
27778 B	B3V	0.37	5.30 ± 0.15[b]	2.20 ± 0.10[b]	9.75 ± 0.78	4.82 ± 0.64	4.90 ± 0.30	9.30 ± 0.30	3.38 ± 1.97	10.48 ± 2.44[x]
34078 G/B	O9.5Ve	0.49	1.72 ± 0.27[c]	0.86 ± 0.21[c]	16.75 ± 1.30	11.28 ± 0.50	27.80 ± 2.64	43.05 ± 2.65	2.73 ± 0.32	5.72 ± 0.21
147889 u	B2III/IV	1.02	12.48 ± 1.74	7.52 ± 1.68	20.07 ± 1.20	15.02 ± 0.98	16.07 ± 0.93[x]	24.37 ± 0.82	2.71 ± 0.40	4.46 ± 0.70[x]
148688 u	B1Ia	0.55	0.92 ± 0.45	0.81 ± 0.54	3.83 ± 0.20	2.75 ± 0.20	13.41 ± 0.65[x]	23.21 ± 0.84	0.38 ± 0.10	1.20 ± 0.20
149757 u	O9.5V	0.28	2.01 ± 0.67	1.25 ± 0.32	5.45 ± 0.20	3.57 ± 0.10	13.90 ± 1.70[x]	23.56 ± 2.10	2.58 ± 0.12	8.32 ± 0.21
151932 u	WN7	0.50	4.46 ± 0.71	2.13 ± 0.54	5.97 ± 0.78	3.60 ± 0.45	6.93 ± 1.60	13.39 ± 1.20	2.56 ± 0.20	7.20 ± 0.40
152270 u	WC7	0.50	1.95 ± 0.64	2.13 ± 0.70	3.52 ± 0.43	2.69 ± 0.45	11.56 ± 0.54	22.31 ± 0.93	1.47 ± 0.31	5.00 ± 0.43
154368 u	O9Ia	0.80	8.21 ± 1.20	5.24 ± 0.86	12.24 ± 1.10	9.32 ± 0.40	10.53 ± 0.79	17.89 ± 0.79	2.05 ± 0.47	5.92 ± 0.67[x]
154811 u	O9.5Ib	0.66	2.43 ± 0.70	1.64 ± 0.50	5.03 ± 0.34	3.12 ± 0.56	18.69 ± 1.23[x]	31.86 ± 1.43	0.18 ± 0.10	0.49 ± 0.20
163800 h/u	O7	0.57	3.71 ± 0.82	2.46 ± 0.78	6.85 ± 0.30	5.16 ± 0.40	7.79 ± 0.41	13.49 ± 0.43	2.87 ± 0.24	9.13 ± 0.31
164794 u	O4V	0.36	1.55 ± 0.40	1.00 ± 0.65	2.29 ± 0.54	1.83 ± 0.34	4.67 ± 0.34	9.32 ± 0.54	0.27 ± 0.12	0.84 ± 0.25
169454 u	B1Ia	1.10	4.89 ± 0.85	2.99 ± 0.72	8.51 ± 0.54	6.47 ± 0.43	9.22 ± 0.54	16.89 ± 1.23	2.91 ± 0.54	9.32 ± 0.80[x]

With supperscript we refer to data concerning the OH molecule from the literature: [a] – Chaffee & Lutz (1976); [b] – Felenbok & Roueff (1996); [c] – Boissé et al. (2005). With x we refer to the measurements of the CN molecule based on the unsaturated B−X (1, 0) transition and the CH^+ molecule based on the unsaturated A−X (1, 0) transition. In the case of HD 27778 we measured the CN A−X (1, 0) transition. Toward HD 34078 we measured the unsaturated CH^+ A−X (2, 0) line at 3745 Å ($W(3745) = 12.23 \pm 0.63$ mÅ).

Table 1 we present identifications of all transitions considered in this paper with their oscillator strengths (f-values) and wavelengths taken from the literature. We used, as far as possible, weak, unsaturated lines to estimate molecular column densities.

Most of our observational material, presented in Table 2, was obtained using the UVES spectrograph at ESO Paranal in Chile (u) with the resolution R = 80 000. These spectra cover the range from 3040 to 10 400 Å. They were acquired as a part of the "Library of High-Resolution Spectra of Stars across the Hertzsbrung-Russell Diagram" and are available at the website: http://www.sc.eso.org/santiago/uvespop. For more information see Bagnulo et al. (2003). These are the only spectra in which direct measurements of all molecular species of interest are available.

In cases of objects where we found no UVES spectra we took the OH band intensities from the literature and the intensities of other molecular features from our own observations done using two other spectrographs. Spectra of 4 objects were acquired using the fiber-fed echelle spectrograph installed at the 1.8-m telescope of the Bohyunsan Optical Astronomy Observatory (BOAO) in South Korea (B). The spectrograph has three observational modes providing a resolving power of 30 000, 45 000, and 90 000. In all the cases it allows recording of the whole spectral range from ~3500 to ~10 000 Å divided into 75−76 spectral orders. We used the highest resolution mode in our project.

The spectrum of HD 163800 was obtained using HARPS spectrometer (h), fed with the 3.6-m ESO telescope in Chile (see http://www.ls.eso.org/lasilla/sciops/3p6/harps/). This spectrograph allow us to cover the range ~3800−~6900 Å with a resolution of R = 115 000. As the instrument was designed to search for exoplanets, it guarantees very precise wavelength measurements.

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).

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. Using different computer codes to the data reduction procedures reduces the possibility of

Table 3. Positions of interstellar OH lines obtained in this work (a) compared with data from the literature.

HD	Position [Å]	Position [Å]
163 800	3078.443 ± 0.003[a]	3081.665 ± 0.003[a]
169 454	3078.443 ± 0.002[a]	3081.664 ± 0.003[a]
149 757	3078.44[b]	3081.66[b]
24 398	3078.4399[c] + 3078.472[c]	3081.6645[c]

[a] – This work; [b] – Herbig (1968); [c] – Felenbok & Roueff (1996).

inaccuracies following the slightly different ways of dark subtraction, flatfielding, or excision of cosmic ray hits. Most of our spectra from UVES were also taken from the archive as pipeline-reduced products (UV-Visual Echelle Spectrograph user manual) which allowed another check of the precision of the measured wavelengths. In each case the continuum placement and equivalent width measurement, based on a Gaussian fit, was 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.

Table 2 presents equivalent widths ($W(\lambda)$) of all molecular features investigated in this paper. To avoid saturation effects we used the CH B−X transition centered near 3886 Å, CH^+ A−X (1, 0) and (2, 0) transitions at 3957 Å and 3745 Å and the CN B−X (1, 0) transition centered near 3579 Å, and the CN A−X (1, 0) transition centered near 9186 Å (to estimate column densities we used the data presented in Table 1). In the case of CN we observed both B−X (0, 0) and (1, 0) and also A−X (1, 0) transitions choosing the non-saturated features to estimate column densities.

The high quality UVES spectra allow us also to check the central wavelengths of the investigated features of OH (Table 3). The positions of the lines near 3078 and 3082 Å were measured toward two objects (HD 163800 and 169454); their spectra have been moved to the rest wavelength velocity frame using KI and CH lines. The objects do not show any Doppler splitting in interstellar lines (in our spectra). Our rest wavelengths of the OH lines are consistent with those published previously by Herbig (1968) and Felenbok & Roueff (1996). However, our spectra were not of high enough resolution to observe the splitting in the 3078 Å line (see level diagram of OH in Felenbok & Roueff 1996). Lines at 3078.4720 and 3078.4399 Å are blended as was observed by Felenbok & Roueff (1996) using the GECKO instrument (R = 120 000).

Results and discussion

Figure 2 shows the relation between equivalent widths of OH lines at 3078 and 3082 Å. Both lines are the result of Λ type doubling of the lowest energy level in OH. Since their wavelengths are very close, the strength ratio should be very similar to that of their oscillator strengths. The latter, according to Felenbok & Roueff (1996), are equal to 1.05(−3) and 6.48(−4) respectively. Figure 2 clearly demonstrates that the equivalent width ratio matches exactly that of the oscillator strengths. Apparently the latter are estimated properly.

Our measurement of equivalent widths of the 3078 Å feature in the spectrum of HD 149757 gives the value 1.25 ± 0.32 mÅ while that published by Chaffee & Lutz (1977) is equal to 1.1 ± 0.7. Both measurements are thus consistent.

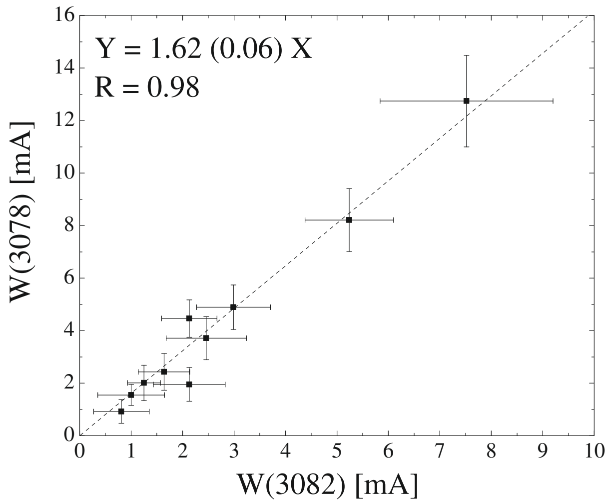

Fig. 2. Correlation plot between equivalent widths of 3078 and 3082 Å lines of interstellar OH as measured in our spectra. This ratio, equal to 1.62 ± 0.06 matches the theoretical expectation (1.62).

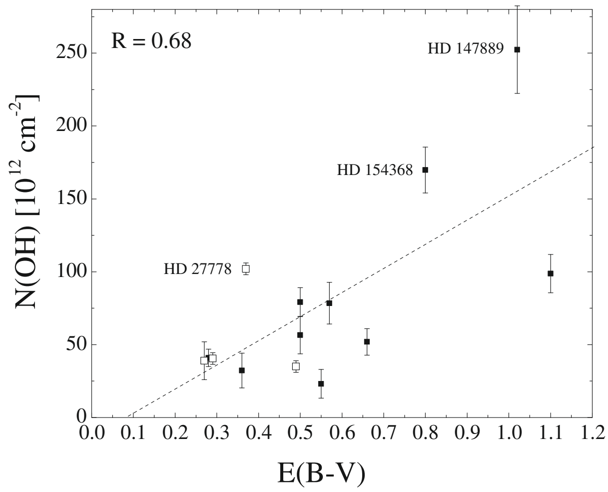

Fig. 3. Relation between column densities of the OH molecule and interstellar reddening $E(B-V)$. The OH molecule is probably not observed at $E(B-V) < 0.08$. With open squares we mark objects where column densities of the OH molecule were taken from the literature.

The equivalent width ratio of 3078 and 3082 Å lines published by Felenbok & Roueff (1996) in the case of HD 27778 (2.4) differs from the theoretical ratio of f-values in case of these transitions (equal to 1.62). In the case of HD 24398 the observed ratio (1.50) is close to the theoretical value. We could not check the above mentioned values, having no sufficiently high quality spectra in the near UV.

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

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

where W_λ and λ are in Å and column density in cm^{-2}. To obtain column density we adopted f-values listed in Table 1. The resulting column densities of each molecule toward target stars are given in Table 4. As already mentioned we used the unsaturated bands of the selected molecules.

In Fig. 3 we present the relation between column densities of OH molecule and $E(B-V)$. The relation, with the correlation coefficient equal to 0.68, is rather poor. It is known that the CH molecule is not observed in regions with $E(B-V) < 0.1$ (Krełowski et al. 1999; Weselak et al. 2004). In the case of the relation between column densities of the H_2 molecule and $E(B-V)$, a sharp transition from small to high values at $E(B-V) = 0.08$ is observed (Savage et al. 1977), due to the fact that H_2 molecules become self-shielded. Self-shielding in the case of H_2 molecules in the radiation field involves dissociation taking place via discrete transitions (which could be self-absorbed) followed by spontaneous dissociation. It is difficult to conclude in Fig. 3 whether we do observe the OH molecule at $E(B-V) < 0.08$. Our result is based on 14 observations (4 of which are taken from the literature).

Figure 4 shows correlation plots between the column density of the OH molecule, obtained as a sum of column densities from two transitions at 3078 and 3082 Å, with the other molecular species being considered here. One point which is outside the relation between column densities of OH and CH molecules, is HD 34078 the object column density of which was taken from Boissé (2005). The column density of HD 154368 published by Spaans et al. (1998) is close to result obtained in this work. We stress that HD 34078 is an atypical object with a high abundance of both CH and CH^+ molecules in relation to $E(B-V)$ (Weselak et al. 2008b, 2009b). Probable changes in abundances of simple molecules were detected in this object (Boissé et al. 2005). However, in this work we obtained column densities of CH and CN molecules based on high-resolution spectra from the GECKO spectrograph (column density of CH^+ was based on a spectrum from BOES), and our measurements are close to those published by Weselak et al. (2008b). In the latter publication we used the spectrum of HD 34078 obtained with the MAESTRO instrument. As a result, in Fig. 4 we present correlation coefficients based on our measurements and those taken from the literature. The best relation, with the correlation coefficient 0.76, is observed in the case of OH and CH molecules, seen in Fig. 4a. If we exclude HD 34078, a relation with correlation coefficient of 0.98 is observed. In Fig. 4b no relation is observed between column densities of OH and the CH cation ($R = 0.06$). The correlation between abundances of OH and CN, with the correlation coefficient equal to 0.68, is close to that between CH and CN molecules – $R = 0.63$ (Weselak et al. 2008b). We emphasize that OH correlates with CH as tightly as H_2 does.

The ratio of ISM abundance of oxygen and carbon, published by Cardelli et al. (1993) in the case of HD 149757−2.21, is close to that of the OH and CH abundance ratio found in this paper (2.62 ± 0.17) using the sample of 10 objects. Carbon is believed to participate in numerous complex molecules which may lower its abundance available to form CH.

In Fig. 5 we present the relation between column densities of the OH molecule and molecular hydrogen. It is difficult to answer the question of whether this relation is linear or not as it is based on six data-points mostly taken from the literature. If a linear relation exists, it needs to be improved using more observations (HD 34078 also misses the relation in this case).

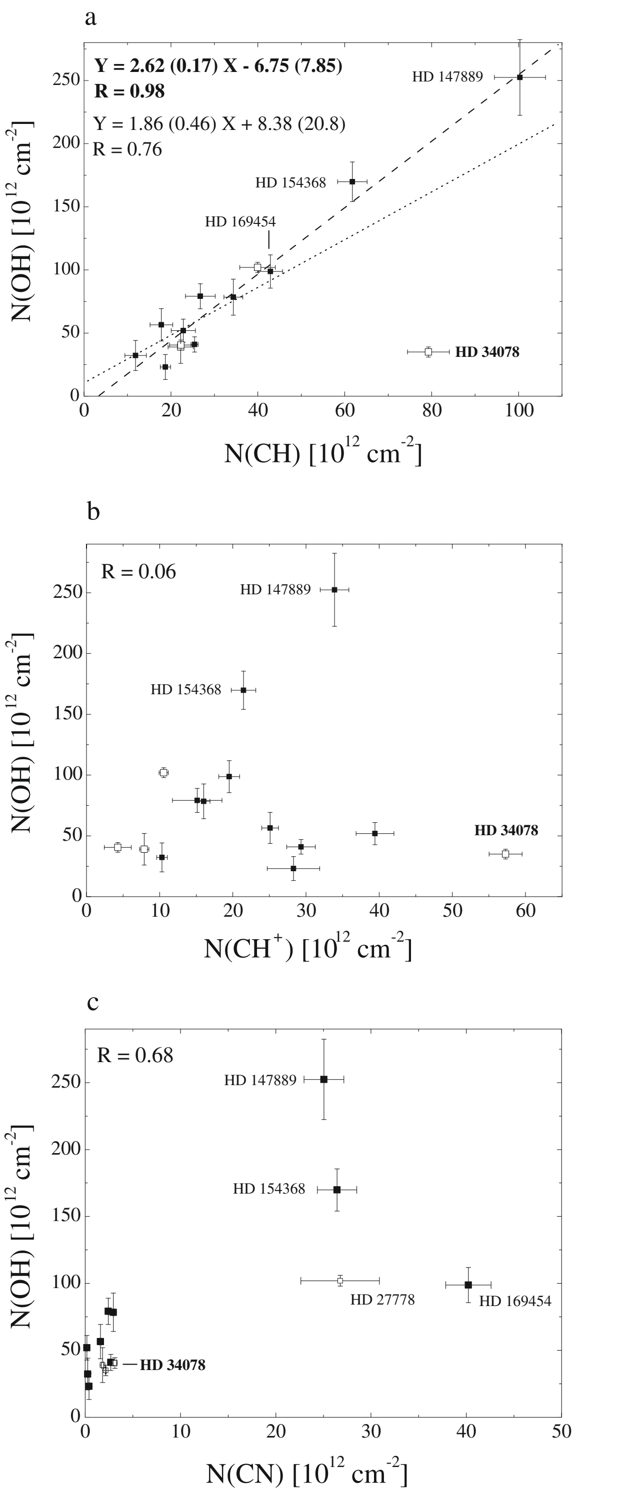

Fig. 4. Column density of OH plotted vs. those of other simple molecular species: CH **a)**, CH^+ **b)** and CN **c)**. Filled squares – our determinations of the OH abundance, open squares – literature data. To calculate correlation coefficients we used all the measurements in each case. In Fig. 4a with the dashed line we present the relation with one data-point excluded – HD 34078 (boldface). In this case the boldfaced relation is very good with the correlation coefficient equal to 0.98.

Conclusions

The above considerations led us to infer the following conclusions:

1. The column densities of both OH and CH molecules are closely related as seen in Fig. 4a. This relation suggests that both species originate and are preserved in the same environments. One atypical object, HD 34078, misses the relation between column densities of OH and CH molecules.
2. Interstellar molecules such as H_2, CH and OH seem to be closely connected in translucent clouds. However, our observational results need to be confirmed with additional observations.

Table 4. Calculated total column densities of the observed interstellar features.

HD/Obs	N(OH) $[10^{12}$ cm$^{-2}]$	N(CH) $[10^{12}$ cm$^{-2}]$	N(CH$^+$) $[10^{12}$ cm$^{-2}]$	N(CN) $[10^{12}$ cm$^{-2}]$	$N(H_2)$ $[10^{20}$ cm$^{-2}]$
23180 B	39.00 ^{a}	22.24 ± 2.91	7.89 ± 0.63	1.82 ± 0.12	4.00^g
24398 B	40.50 ± 4.00^b	22.30 ± 2.61	4.28 ± 1.84	3.12 ± 0.18	4.70^g
27778 B	102.00 ± 4.00^b	39.93 ± 4.10	10.55 ± 0.63	26.76 ± 4.12^f	6.17^h
34078 G/B	35.00± 4.00^c	79.27 ± 4.82	57.28 ± 2.25$^{d'}$	2.16 ± 0.05	6.40^c
147889 u	252.36 ± 30.74	100.33 ± 5.87	33.90 ± 1.96^d	25.06 ± 2.09^e	
148688 u	23.11 ± 9.88	18.73 ± 1.18	28.29 ± 3.59^d	0.39 ± 0.04	
149757 u	40.98 ± 6.00	25.44 ± 0.82	29.32 ± 1.96^d	2.68 ± 0.05	4.40^g
151932 u	79.15 ± 9.88	26.76 ± 3.42	15.13 ± 3.38	2.43 ± 0.07	
152270 u	56.54 ± 12.81	17.79 ± 2.61	25.10 ± 1.14	1.59 ± 0.10	
154368 u	169.84 ± 15.73	61.75 ± 4.10	21.46 ± 1.67	26.44 ± 2.07^e	14.45^h
154811 u	51.90 ± 9.15	22.85 ± 2.79	39.43 ± 2.59^d	0.17 ± 0.04	
163800 h/u	78.43 ± 14.27	34.36 ± 2.16	16.02 ± 0.86	2.96 ± 0.08	
164794 u	32.26 ± 11.89	11.86 ± 2.47	10.32 ± 0.72	0.27 ± 0.06	
169454 u	98.76 ± 13.17	42.90 ± 2.79	19.50 ± 1.42	40.22 ± 2.38^e	

We designate data from the literature as follows: ^{a} – Roueff (1996); ^{b} – Felenbok & Roueff (1996); ^{c} – Boissé et al. (2005). To avoid saturation effects in the case of CH$^+$ and CN molecules we used the unsaturated: ^{d} – CH$^+$ A−X (1, 0) line at 3957 Å; d' – CH$^+$ A−X (2, 0) line at 3745 Å; ^{e} – CN B−X (1, 0) band at 3579 Å; ^{f} – CN A−X (1, 0) band at 9186 Å. Data on H_2 taken from ^{g} – Savage et al. (1977); ^{h} – Rachford et al. (2002); ^{c} – Boissé et al. (2005).

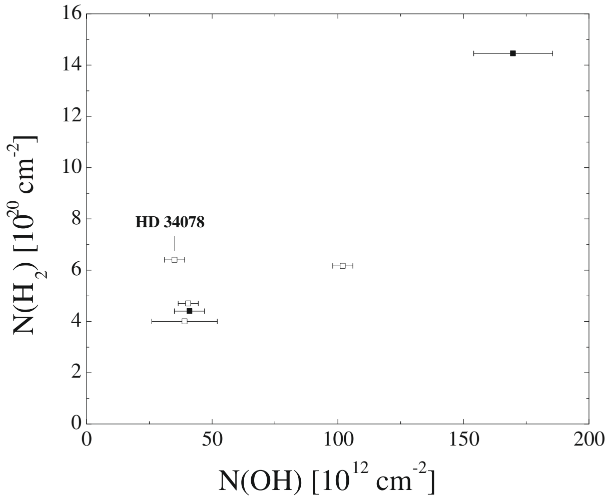

Fig. 5. Interstellar H_2 column density (from the literature) vs. that of OH. Filled squares – our measurements; open squares – the literature data. Note HD 34078 – the object probably also lies outside the relation between column densities of H_2 and OH.

3. Other molecular species, such as the CN or the CH cation seem to be formed in other reaction pathways since their column densities do not correlate with those of H_2, CH and OH.

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