Interstellar NH molecule in translucent sightlines

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ABSTRACT

Abundance relationships between the interstellar NH molecule and other diatomic species are presented based on 10 currently available sightlines (two of them taken from the literature). Spacial correlations between column densities of diatomic molecules suggest that the NH molecule is more closely related to neutral species than it is to CH^+.

Key words: ISM: molecules.

1 INTRODUCTION

Interstellar NH is expected to play a crucial role in the nitrogen chemistry of diffuse molecular clouds (Crutcher & Watson 1976). It was detected in the interstellar medium (ISM) towards two stars, HD 27778 and 24398, by Meyer & Roth (1991), and towards HD 149757 by Crawford & Williams (1997). Two very weak features near 3354 and 3358 Å of the $A^3\Pi_i - X^3\Sigma^-$ (0, 0) band lie in the spectral region where poor atmospheric transmission and interstellar extinction combine to make detection difficult. However, the NH molecule has frequently been detected in the spectra of cool stars (Lambert & Beer 1972) and in the spectra of comets (Swings, Elvey & Babcock 1941).

The detections detailed in the literature do not allow us to analyse relationships between NH and other simple interstellar molecules: the sample of three objects is too small. We found a way to extend the sample towards eight targets, seven of which are new, using the high-resolution UVES spectrograph. Such a sample allows us to examine the relationships between the column densities of the NH molecule and those of simple diatomic species such as CN, CH and CH^+, which were identified in the ISM by McKellar (1940a,b). It is known that the CH molecule is closely related to molecular hydrogen (H_2) and OH (Mattila 1986; Weselak et al. 2004, 2009b). The relationship between the column densities of interstellar CH^+ and H_2 shows a large scatter, suggesting the lack of spacial relationship between these two molecules (Weselak et al. 2008a).

Recently, it was shown (Weselak et al. 2008b) that the CH molecule is quite strongly correlated with narrow diffuse interstellar bands (DIBs). Column density relationships between simple molecular species may play an important role in the identification of DIB carriers, which might possibly be complex molecules. However, the small size of the currently available sample of objects makes this task very difficult. Here we extend the list of objects towards which NH is detected and try to find possible relationships between all considered molecular species.

2 THE OBSERVATIONAL DATA

Table 1 lists all transitions in all molecular species considered in this work, along 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. The H_2 molecule was excluded from Table 1 as its column densities were taken from the literature.

Most of our observational material, presented in Table 2, was obtained using the UVES spectrograph at ESO Paranal in Chile with a resolution of $R = 80\,000$. 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 for which direct measurements of all molecular species of interest are available.

For objects for which we found no UVES spectra we took the NH band intensities from the literature, and the intensities of other molecular features from our own observations obtained using two other spectrographs. Spectra of two objects were acquired using the fibre-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 cases it allows the whole spectral range from ∼3500 to ∼10 000 Å to be recorded divided into 75–76 spectral orders. We used the highest-resolution mode in our study.

The spectrum of HD 163800 was also obtained using the 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 covers the range ∼3800 to ∼6900 Å with a resolution of

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Table 1. Adopted molecular parameters. References: 1, this work; 2, Meyer & Roth (1991); 3, Weselak et al. (2009b); 4, Felenbok & Roueff (1996); 5, Gredel, van Dishoeck & Black (1993); 6, Weselak et al. (2009a); 7, Meyer, Roth & Hawkins (1989); 8, van Dishoeck & Black (1989),

Species	Vibronic band	Rotational lines	Position [Å]	Ref.	f-value	Ref.
NH	$A^3\Pi_i - X^3\Sigma^-$ (0, 0)	$^RQ_{21}(0)$	3353.924	1	0.00240	2
	(0, 0)	$R_1(0)$	3358.053	1	0.00410	2
OH	$A^2\Sigma^+ - X^2\Pi_i$ (0, 0)	$Q_1(3/2)+^QP_{21}(3/2)$	3078.443	3	0.00105	4
	(0, 0)	$P_1(3/2)$	3081.6645	3	0.000648	4
CH	$B^2\Sigma^- - X^2\Pi$ (0, 0)	$Q_2(1)+^QR_{12}(1)$	3886.409	5	0.00320	5
	(0, 0)	$^PQ_{12}(1)$	3890.217	5	0.00210	5
CH^+	$A^1\Pi - X^1\Sigma^+$ (0, 0)	$R(0)$	4232.548	5	0.00545	5
	(1, 0)	$R(0)$	3957.689	6	0.00342	6
CN	$B^2\Sigma^+ - X^2\Sigma^+$ (1, 0)	$R(0)$	3579.963	7	0.00300	7
	(1, 0)	$R(1)$	3579.453	7	0.00200	7
	$B^2\Sigma^+ - X^2\Sigma^+$ (0, 0)	$R(0)$	3874.608	7	0.03420	7
	(0, 0)	$R(1)$	3873.998	7	0.02280	7
	$A^2\Pi - X^2\Sigma^+$ (1, 0)	$R_1(0)$	9186.935	8	0.000792	8
	(1, 0)	$R_1(1)$	9183.216	8	0.000501	8

Table 2. Positions of interstellar NH lines. References: a, this work; b, Herbig (1968); c, air wavelengths calculated from the vacuum values of Dixon (1959) using Edlen's (1953) correction for refraction.
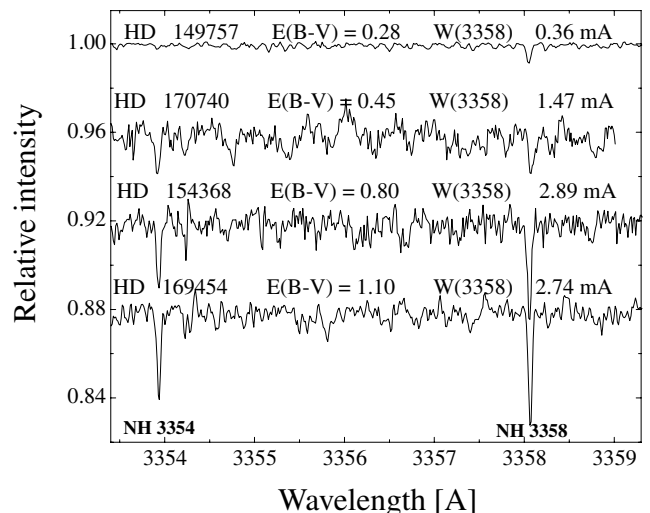
HD	Position [Å]	Position [Å]	Ref.
149757	3353.924 ± 0.002	3358.052 ± 0.002	a
163800	3353.924 ± 0.002	3358.053 ± 0.003	a
169454	3353.923 ± 0.003	3358.053 ± 0.003	a
	3353.924 ± 0.002	3358.053 ± 0.003	a
	3353.92	3358.06	b
	3353.9235	3358.0525	c

Figure 1. A–X system of the NH molecule near 3354 and 3358 Å in the spectra of four objects characterized by different $E(B - V)$s. Note the increase of the NH 3358-Å line equivalent width with interstellar reddening.

$R = 115\,000$. As an instrument designed to search for exoplanets, it guarantees very precise wavelength measurements.

All the spectra were reduced using the standard packages MI-DAS 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 for the data reduction procedures reduces the possibility of inaccuracies arising from the slightly different ways of dark subtraction, flat-fielding, 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, were performed as in Weselak et al. (2009a). Recall that, owing to the very low density of interstellar clouds, the only efficient line-broadening mechanism is the Doppler one.

In Fig. 1 we present the spectra of four objects (HD 149757, 154368, 169454 and 170740) in the spectral region of the NH lines near 3354 and 3358 Å after continuum placement performed as in Weselak et al. (2009a). The intensity of both features seems to grow, as would be expected, with the reddening. Unfortunately, both lines are very weak and thus are available in only a few objects.

The high quality of the UVES spectra means that we can check the central wavelengths of the investigated features of NH (Table 2). The positions of the lines near 3354 and 3358 Å were measured towards three objects (HD 149757, 163800 and 169454); their spectra have

been moved to the rest-wavelength velocity frame using K I and CH lines. The objects do not show any Doppler splitting in interstellar lines (in our spectra). Our rest wavelengths of the NH lines are consistent with those published previously by Herbig (1968) and Meyer & Roth (1991). The latter work presents air wavelengths calculated from the vacuum values of Dixon (1959).

3 RESULTS AND DISCUSSION

Table 3 contains the equivalent widths ($W(\lambda)$) of all molecular features considered in this work. To avoid saturation effects, we used the CH B–X (0, 0) transition near 3386 Å, the CH^+ A–X (1, 0) transition near 3957 Å, and the CN A–X (1, 0) transition near 9187 Å and B–X (1, 0) transition near 3580 Å. The B–X (0, 0) transition of CN near 3875 Å was used only if no saturation effects were apparent. We compared our measurements of the 3354- and 3358-Å NH lines with those published in the literature for HD 149757. Our results (0.20 ± 0.12 and 0.36 ± 0.06 mÅ) are consistent

Table 3. Measured equivalent widths of interstellar features. References: a, Meyer & Roth (1991); b, Felenbok & Roueff (1996). The *x* denotes measurements of the CN molecule based on the unsaturated B–X (1, 0) transition and of CH+ based on the unsaturated A–X (1, 0) transition. In the case of HD 27778 we measured the CN A–X (1, 0) transition.

HD/Obs	Sp/L	Ebv	NH 3354 [mÅ]	NH 3358 [mÅ]	OH 3078 [mÅ]	OH 3082 [mÅ]	CH 3886 [mÅ]	CH 3890 [mÅ]	CH+ 3957 [mÅ]	CH+ 4232 [mÅ]	CN R1 [mÅ]	CN R0 [mÅ]
24398 B	B1Iab	0.29	0.2(0.1)[a]	0.37(0.08)[a]	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	0.7(0.3)[a]	1.1(0.3)[a]	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]
147889 u	B2III/IV	1.02	1.36(0.2)	2.46(0.23)	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]
149757 u	O9.5V	0.28	0.20(0.12)	0.36(0.06)	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		1.66(0.27)	4.46(0.71)	2.13(0.54)	5.75(0.41)	4.01(0.32)	6.93(1.60)	13.39(1.20)	2.56(0.20)	7.20(0.40)
152236 u	B1Iape	0.65	0.51(0.16)	0.74(0.16)	3.50(0.44)	2.41(0.34)	5.34(0.45)	4.15(0.56)	11.88(0.45)	17.11(0.40)	2.55(0.34)	8.06(0.34)
154368 u	O9Ia	0.80	1.62(0.20)	2.89(0.24)	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]
163800 h/u	O7	0.57	0.50(0.20)	0.64(0.10)	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)
169454 u	B1Ia	1.10	1.68(0.11)	2.74(0.12)	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]
170740 u	B2V	0.45	1.00(0.34)	1.47(0.32)	1.97(0.43)	1.73(0.31)	5.10(0.29)	2.84(0.20)	8.01(0.23)	13.63(0.26)	0.66(0.14)	1.92(0.17)[x]
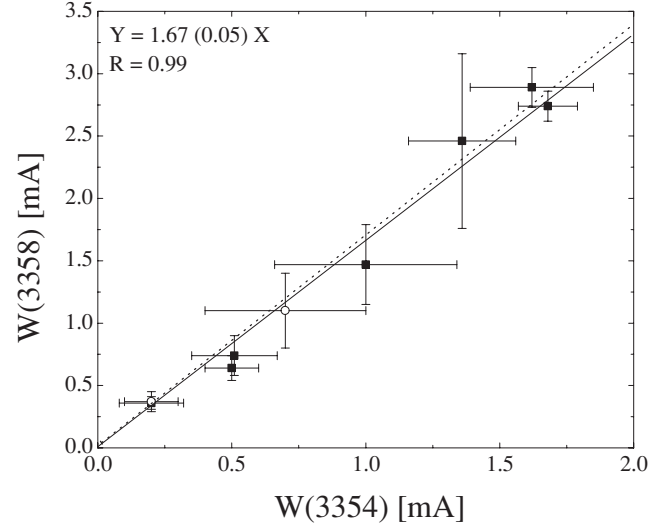
Figure 2. Correlation plot between the equivalent widths of the 3358- and 3354-Å lines of the NH molecule measured in our spectra (filled squares) and taken from the literature (circles). The solid line gives the fit to all data points, and the dotted one gives the ratio of the oscillator strengths (1.71) in Meyer & Roth (1991).

Table 4. Oscillator strengths and intensity ratios of the NH lines at 3358 and 3354 Å based on data from the literature. References: a, Herbig (1968); b, Meyer & Roth (1991); c, Owono Owono et al. (2008). *W*, equivalent width.

f(3358)	f(3354)	W(3358)/W(3354)	Ref.
0.0043	0.0025	1.72	a
0.0041	0.0024	1.71	b
0.0043	0.0020/0.0016	2.15/2.69	c

with those published by Meyer & Roth (1991) (0.2 ± 0.1 and 0.37 ± 0.08, respectively) and also by Crawford & Williams (1997) in the case of 3358 (0.36 ± 0.05 mÅ).

In Fig. 2 we present the relationship between the equivalent widths of the NH lines at 3358 and 3354 Å. Because the features apparently do not show saturation effects their strength ratio should be very similar to that of the oscillator strengths. The latter, according to Meyer & Roth (1991), are equal to 4.1(−3) and 2.4(−3), respectively. In Table 4 we present the oscillator strengths of the NH lines at 3354 and 3358 Å given in the literature, along with calculated strength ratios. Fig. 2 clearly demonstrates that the equivalent-width ratio (1.67 ± 0.05) is close to those of the oscillator strengths of 1.71 and 1.72, based on the publications of Herbig (1968) and Meyer & Roth (1991), respectively. This confirms that our measurements are correct, despite the relatively low signal-to-noise ratio inside the features. This result also confirms that observed features of the NH molecule at 3358 and 3354 Å are unsaturated.

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 the column density is in cm^{-2}. To obtain the NH column density we adopted the f-values listed in

Table 5. Calculated total column densities of the observed interstellar features. References: (*a*) Meyer & Roth (1991); (*b*) Felenbok & Roueff (1996). To avoid saturation effects in the case of CH$^+$ and CN we used the unsaturated (*c*) CH$^+$ A–X (1, 0) line at 3957 Å ; (*d*) CN B–X (1, 0) band at 3579 Å ; (*e*) CN A–X (1, 0) band at 9186 Å . Data on H$_2$ are taken from (*f*) Savage et al. (1977); (*g*) Rachford et al. (2002); (*h*) Rachford et al. (2009).

HD	N(NH) [10^{12} cm^{-2}]	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}]
24398	0.90[a]	40.50 ± 4.00[b]	22.30 ± 2.61	4.28 ± 1.84	3.12 ± 0.18	4.70[f]
27778	2.70 ± 1.20[a]	102.00 ± 4.00[b]	39.93 ± 4.10	10.55 ± 0.63	26.76 ± 4.12[e]	6.17[g]
147889	5.85 ± 0.96	252.36 ± 30.74	100.33 ± 5.87	33.90 ± 1.96[c]	25.06 ± 2.09[d]	
149757	0.76 ± 0.25	40.98 ± 6.00	25.44 ± 0.82	29.32 ± 1.96[c]	2.68 ± 0.05	4.40[f]
151932	4.06 ± 1.00	79.15 ± 9.88	26.76 ± 3.42	15.13 ± 3.38	2.43 ± 0.07	
152236	1.97 ± 0.67	75.62 ± 6.22	27.24 ± 3.04	22.43 ± 0.97	2.62 ± 0.06	5.37[h]
154368	6.92 ± 1.00	169.84 ± 15.73	61.75 ± 4.10	21.46 ± 1.67	26.44 ± 2.07[d]	14.45[g]
163800	2.18 ± 0.42	78.43 ± 14.27	34.36 ± 2.16	16.02 ± 0.86	2.96 ± 0.08	
169454	6.86 ± 0.50	98.76 ± 13.17	42.90 ± 2.79	19.50 ± 1.42	40.22 ± 2.38[d]	
170740	3.89 ± 1.42	49.40 ± 5.67	22.02 ± 1.39	16.34 ± 0.49	8.55 ± 2.38	

Table 1. The resulting column densities of each molecule towards target stars are given in Table 5. In each case we calculated the column density of the NH molecule as an average obtained using the 3354- and 3358 -Å lines. In the case of HD 151932, the column density is based on the measurement of the latter line (no measurement of the former was available). As already mentioned, we used only unsaturated bands of the selected molecules (i.e. of CH, CH$^+$, OH and CN). It is always risky to deal with saturated features using the curve of growth method because we usually do not know the broadening parameter b, which can be measured only in ultra-high-resolution spectra (Crawford 1995).

In Fig. 3 we present the relationship between the column densities of the NH molecule and $E(B - V)$, characterized by a correlation coefficient equal to 0.84. Since the publications of Krełowski et al. (1999) and Weselak et al. (2004) it has been well known that the CH molecule is not observed for $E(B - V) < 0.1$. In the case of the relationship between the column density of the H$_2$ molecule and $E(B - V)$, a sharp transition from low to high H$_2$ abundance

is observed at $E(B - V) = 0.08$ (Savage et al. 1977), owing to the fact that H$_2$ molecules become self-shielded. It is difficult to ascertain from Fig. 3 whether a similar phenomenon is observed in the case of the NH molecule because the sample is small and contains only reasonably heavily reddened targets. We have collected observations of NH column densities for 10 objects (two of which are taken from the literature). This is still a rather small sample, but it is unlikely that we will be able to extend it soon.

Fig. 4 presents correlation plots between the column density of the NH molecule and that of CN, CH$^+$, CH and OH, respectively. The best relationship, with a correlation coefficient equal to 0.78, is observed between the column densities of NH and CN molecules. We observe similar relationships between the column density of the NH molecule and that of other neutral species such as CH and OH (correlation coefficients equal to 0.64 and 0.69, respectively). The weak correlation (0.32) between the abundances of interstellar NH and CH$^+$, with a correlation coefficient of 0.32, suggests that there is no connection between the chemistry of NH and CH$^+$ in interstellar clouds.

It is well known, from the chemical models discussed extensively in Wagenblast et al. (1993), that the predicted rate of NH formation from grain surface reactions is much higher than that possible from pure gas-phase chemistry. Results presented in this work clearly confirm this suggestion. In Fig. 5 we present the relationship between the column densities of the NH molecule and molecular hydrogen column densities taken from the literature. It is difficult to ascertain whether this relationship is linear or not as it is based on only five data points. If a linear relationship exists, it needs to be improved using more observations. However, because H$_2$ is closely related to CH, it might be expected that the relationship between NH and H$_2$ should be very similar to that between NH and CH.

4 CONCLUSIONS

The above considerations led us to infer the following conclusions.

(i) The abundance of the NH molecule is reasonably well correlated with $E(B - V)$, with the correlation coefficient equal to 0.84 (Fig. 3). This is consistent with the possible creation of NH by means of dust surface chemistry.

(ii) The NH molecule is more closely related to CN (and other neutral species) than to CH$^+$. Because H$_2$ is believed to originate in surface reactions this may support the idea of a catalytic role of dust grains in the formation of NH molecules. The CH molecule may
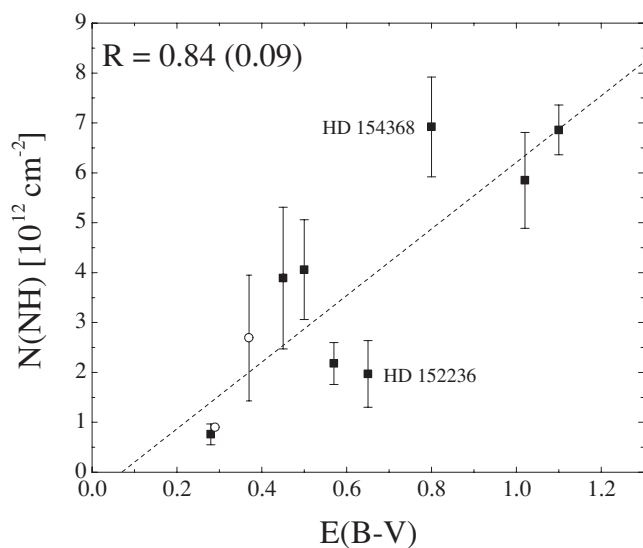
Figure 3. Relationship between column densities of the NH molecule and interstellar reddening $E(B - V)$. Open symbols mark the objects with column densities of the NH molecule taken from the literature.
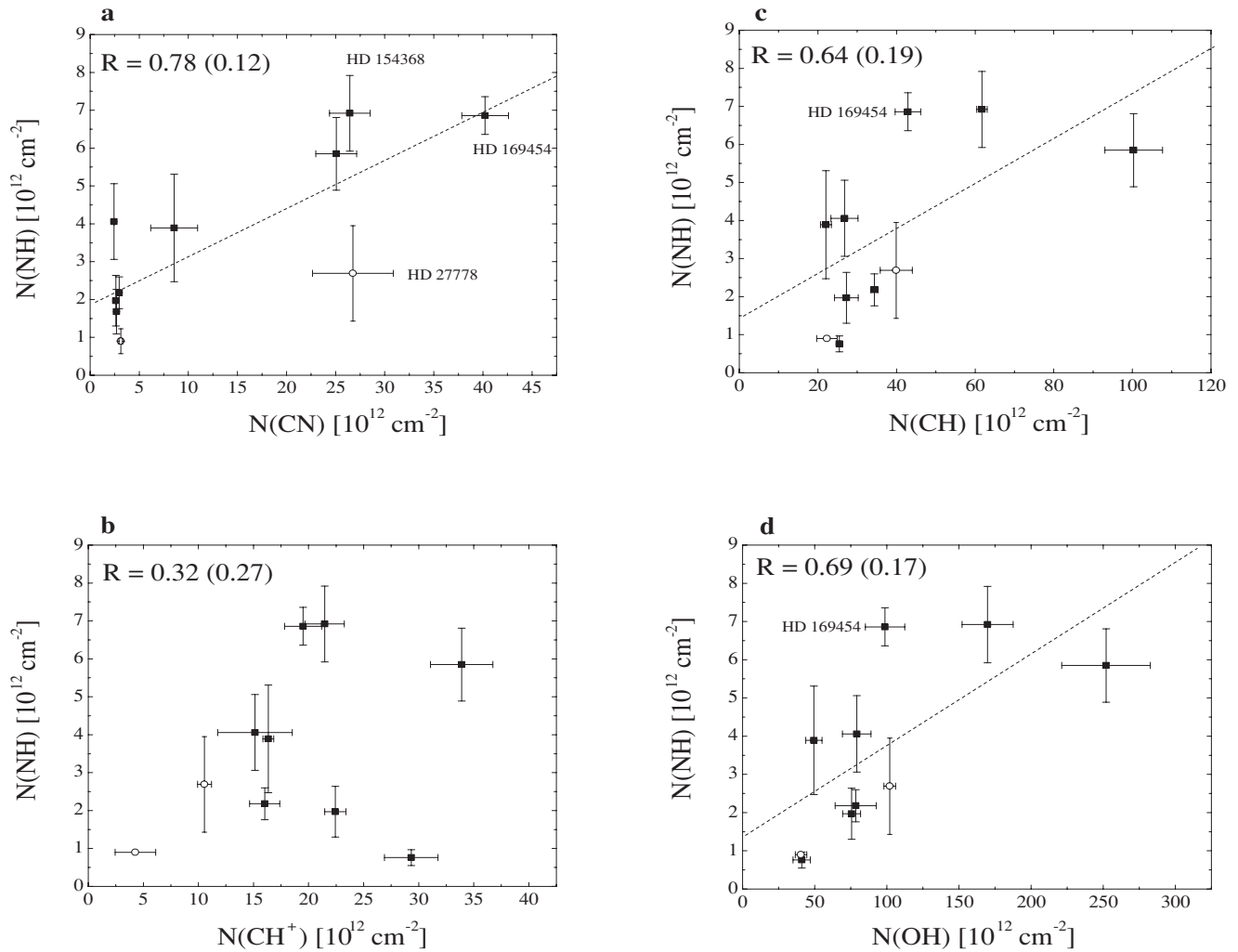
Figure 4. Column density of NH versus those of other simple molecular species: (a) CN, (b) CH$^+$, (c) CH and (d) OH. Filled squares denote our determinations of the NH abundance, and circles denote data from the literature. To calculate the correlation coefficients (errors in brackets) we used all measurements in each case. The most strongly related column densities are those of the NH and CN molecules (a).
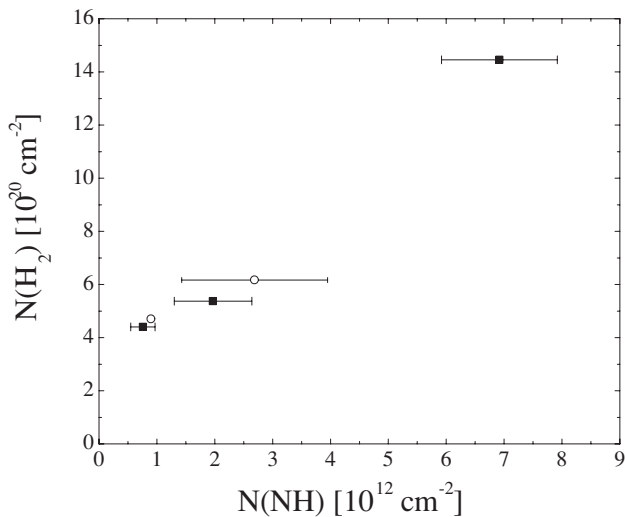
Figure 5. Interstellar column density of H$_2$ (from the literature) versus that of NH. Filled squares denote our measurements, and circles denote data from the literature.

be used as an OH and H$_2$ tracer, as its features are easily accessible and closely related to the abundances of hydrogen and hydroxyl (Weselak et al. 2009b).

REFERENCES

Bagnulo S., Jehin E., Ledoux C., Cabanac R., Melo C., Gilmozzi R., The ESO Paranal Science Operations Team, 2003, Messenger, 114, 10
Crawford I. A., 1995, MNRAS, 277, 458
Crawford I. A., Williams D. A., 1997, MNRAS, 291, L53
Crutcher R. M., Watson W. D., 1976, ApJ, 209, 778
Dixon R. N., 1959, Can. J. Phys., 37, 1171
Edlen B., 1953, J. Opt. Soc. Am., 43, 339
Felenbok P., Roueff E., 1996, ApJ, 465, L57
Galazutdinov G. A., 1992, Prep. Spets. Astrof. Obs., No 92.
Gredel R., van Dishoeck E. F., Black J. H., 1993, A&A, 269, 477
Herbig G. H., 1968, ZA, 68, 243

Krełowski J., Ehrenfreund P., Foing B. H., Snow T. P., Weselak T., Tuairisg S. Ó., Galazutdinov G. A., Musaev F. A., 1999, A&A, 347, 235

Lambert D. L., Beer R., 1972, ApJ, 177, 541

McKellar A., 1940a, PASP, 52, 187

McKellar A., 1940b, PASP, 52, 312

Mattila K., 1986, A&A, 160, 157

Meyer D. M., Roth K. C., 1991, ApJ, 376, L49

Meyer M. D., Roth K. C., Hawkins I., 1989, ApJ, 343, L1

Owono Owono L. C., Ben Abdallah D., Jaidane N., Ben Lakhdar Z., 2008, J. Chem. Phys., 128, 43090

Rachford B. L. et al., 2002, ApJ, 577, 221

Rachford B. L. et al., 2009, ApJS, 180, 125

Roueff E., 1996, MNRAS, 279, L37

Savage B. D., Bohlin R. C., Drake J. F., Budich W., 1977, ApJ, 216, 291

Swings P., Elvey C. T., Babcock W., 1941, ApJ, 94, 320

van Dishoeck E. F., Black J. H., 1989, ApJ, 340, 273

Wagenblast R., Williams D. A., Millar T. J., Nejad L. A. M., 1993, MNRAS, 260, 420

Weselak T., Galazutdinov G. A., Musaev F. A., Krełowski J., 2004, A&A, 414, 949

Weselak T., Galazutdinov G. A., Musaev F. A., Krełowski J., 2008a, A&A, 479, 149

Weselak T., Galazutdinov G. A., Musaev F. A., Krełowski J., 2008b, A&A, 484, 381

Weselak T., Galazutdinov G. A., Musaev F. A., Beletsky Y., Krełowski J., 2009a, A&A, 495, 189

Weselak T., Galazutdinov G. A., Beletsky Y., Krełowski J., 2009b, A&A, 499, 783

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