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Identification of solar vibration-rotation lines of NH and the solar nitrogen abundance

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Abstract. High resolution solar spectra obtained from the ATMOS Fourier Transform Spectrometer (Spacelab 3 flight on April 29–May 6, 1985) have permitted us to detect for the first time vibration-rotation lines of NH from the $X^3\Sigma^-$ state near $\lambda 3\mu\text{m}$. Using recent theoretical results for the transition probabilities of 23 selected measured lines of the 1–0 and 2–1 bands, we derive a solar abundance of nitrogen of 8.06 ± 0.07 . This value is compared with the result derived from N I lines and agrees with the abundance obtained from the $3s-3p$, $3p-3d$ and $3s'-3p'$ transitions, $A_N = 8.00 \pm 0.09$. Our final recommended solar abundance of nitrogen is $A_N = 8.00 \pm 0.05$ (see Note added in proof).

Key words: abundances: solar – molecular oscillator strengths – solar spectrum

1. Introduction

Five vibration-rotation (V-R) lines within the ground state $X^3\Sigma^-$ of NH near $\lambda 3\mu\text{m}$ were tentatively identified in the spectrum of the M supergiant α Ori by Lambert and Beer (1972) before any laboratory detection of these lines. Subsequent analysis of high-resolution spectra have confirmed the presence of NH vibration-rotation lines in spectra of cool oxygen-rich and in carbon-rich giant and supergiant stars: Lambert et al. (1984, 1986); Ridgway et al. (1984). Only recently has the vibration-rotation spectrum been detected and rotationally analysed in the laboratory [Sakai et al. (1982); Bernath and Amano (1982); Boudjaadar et al. (1986)] confirming the assignments from stellar spectra. Milligan and Jacox (1979) observed the V-R transition in a matrix experiment.

The ATMOS (Atmospheric Trace Molecule Spectroscopy) experiment onboard Spacelab 3 (April 29–May 6, 1985; Farmer, 1987) also recorded high-resolution and low-noise solar spectra, between 2 and $16\mu\text{m}$, free from any telluric absorption. This prompted us to carry out a search for the weak infrared vibration-rotation solar lines of NH and to use the lines to determine the solar N abundance. Published estimates of the N abundance (Lambert, 1978) are based on the permitted high excitation atomic

(N I) lines and the lines of the electronic transition $A^3\Pi_i-X^3\Sigma^-$ of NH which were identified in the solar ultraviolet photospheric spectrum, shortly after Funke's (1935) pioneering laboratory analysis. Lambert (1978) discussed the problems associated with the nitrogen abundance indicators (see also Sect. 3.2). Our work presents an independent determination of the N abundance via the weak NH V-R lines together with a rediscussion of the N I lines.

2. Solar observations and line positions

Accurate frequencies of the NH V-R lines were first measured in the laboratory by Bernath and Amano (1982) who reported results for 29 transitions of the 1–0 band from $P(4)$ to $R(5)$. More extensive measurements of the fundamental sequence from the 1–0 to 5–4 bands were described by Boudjaadar et al. (1986). These authors give predicted frequencies for lines they cannot resolve because of the sources they used to generate NH. Since solar V-R lines are detectable beyond the rotational limits covered by Boudjaadar et al. (e.g. $N'' = 19$ for the 1–0 band), we used the accurate term values given by Brazier et al. (1986) for the $v = 0, 1$ and 2 levels of $X^3\Sigma^-$ to predict all R_i - and P_i -line positions ($i = 1, 2$ and 3) beyond the range covered by Boudjaadar et al. i.e. up to $N'' = 30$ for the 1–0 band, $N'' = 21$ for the 2–1 band and $N'' = 12$ for the 3–2 band. These term values were obtained in the authors' precise reinvestigation of the $A^3\Pi_i-X^3\Sigma^-$ transition. We note that the three components of the R branch R_1, R_2 , and R_3 nearly coincide except at very low N'' -values, whereas the P_1 and P_2 lines are almost coincident with the P_3 line generally displaced at 0.2cm^{-1} from the doublet. More exactly, the minimum separation between the three R_i branches occurs in the interval $N'' = 10-18$ for the 1–0 band and $N'' = 9-15$ for the 2–1 band.

We searched for the NH lines on high resolution (around 0.01cm^{-1}), low-noise ($S/N \sim 500$) and pure (i.e. not contaminated by telluric absorption) solar spectra obtained by the ATMOS Fourier transform spectrometer experiment. These observations were obtained from a small circular region near the solar disk center (more exactly at $\cos\theta = 0.935$).

Our search was restricted to the unresolved $R_1 + R_2 + R_3$ triplets. The absence of even the most intense P lines is readily understood as due to the severe vibration-rotation interaction (see

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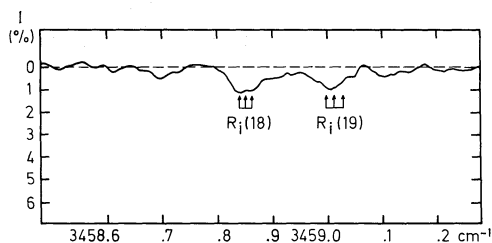


Fig. 1. Solar spectrum around the NH $R_1(18)$ and $R_1(19)$ vibration-rotation lines of the 1–0 band. Arrows indicate the position of the 3 components as measured in the laboratory

below). Good agreement was found between the laboratory frequencies predicted and the ATMOS Doppler-corrected solar frequencies. $R_1(N'')$ lines have been clearly identified up to $N'' = 27$ for the 1–0 band; up to $N'' = 20$ for the 2–1 band; up to $N'' = 18$ for the 3–2 band and up to $N'' = 11$ for the 4–3 band. The NH molecule is identified without any doubt in the solar atmosphere. Figure 1 shows an enlargement of the solar spectrum around the $R_1(18)$ and $R_1(19)$ unresolved components of the 1–0 band. The equivalent width of about forty unblended R “triplets” were measured very carefully. Table 1 gives the results of our measurements for the best lines of the 1–0 (12 lines) and 2–1 (11 lines) bands. The strongest lines of both bands have a central depth of about one and a half percent and an equivalent width of nearly 0.9 mK; the weakest lines measured have only 0.4 mK. Weaker lines including all of the identifications with the 3–2 and 4–3 R branches are clearly present but, since their equivalent widths are subject to considerable uncertainty, we do not list these lines in Table 1. It is clear that our identification of weak NH lines was favoured by the superposition of three branches ($R_1 + R_2 + R_3$) at each N'' -value, which leads to solar lines about three times more intense than expected for a single component.

3. The solar nitrogen abundance

3.1. The NH vibration-rotation lines

The observed equivalent widths of the triplet lines in Table 1 were compared with predicted values derived from synthetic spectra computed using the following principal ingredients: a solar atmosphere model and basic molecular data such as the dissociation energy of NH and the transition probabilities of the V-R lines. The N abundance is the free parameter that is adjusted in order to match the synthetic to the observed equivalent widths.

We adopted a slightly modified solar atmosphere model, that is very similar to Holweger and Müller’s (1974) model in the layers where the NH lines (and also the Ni lines) are formed. The influence of the microturbulent velocity on the weak lines is negligible as expected: a value of 0.9 km s^{-1} has been adopted.

The adopted dissociation energy of NH is that recommended by Bauschlicher and Langhoff (1987) from their elaborate ab initio calculations of CH, NH, and OH: $D_0^0 = 3.37 \pm 0.03 \text{ eV}$. Their predictions of $D_0^0(\text{CH}) = 3.433 \text{ eV}$ and $D_0^0(\text{OH}) = 4.360 \text{ eV}$ are only slightly smaller than the well determined spectroscopic estimates of $D_0^0(\text{CH}) = 3.465 \text{ eV}$ (Brzozowski et al., 1976) and $D_0^0(\text{OH}) = 4.392 \text{ eV}$ (Carlone and Dalby, 1969). Bauschlicher and Langhoff correct their comparable prediction for NH, $D_0^0(\text{NH}) = 3.344 \text{ eV}$, by the average difference between their theoretical and the experimental results for CH and OH and so

obtain $D_0^0(\text{NH}) = 3.37 \text{ eV}$. It is noted by Bauschlicher and Langhoff that other theoretical values are consistent with the recommended $D_0^0(\text{NH})$ – see especially Melius and Binkley (1984).

At present, just one experimental determination of $D_0^0(\text{NH})$ appears to have been made with a demonstrated precision comparable to that claimed by Bauschlicher and Langhoff for their (adjusted) prediction. A study of the predissociation of the $c^1\Pi$ state led Graham and Lew (1978) to a firm upper limit of $D_0^0(\text{NH}) = 3.47 \text{ eV}$. A lower limit, $D_0^0(\text{NH}) = 3.32 \text{ eV}$, was set by Hofzumahaus and Stuhl (1985) from the upper limit to the heat of formation of NH estimated from a study of laser photolysis of NH_3 . These limits bracket the recommended theoretical value. Recently, Ervin and Armentrout (1987) combined their accurate determination of the reaction endothermicity for the process $\text{N}^+ (^3P) + \text{H}_2 \rightarrow \text{NH}^+ + \text{H}$ with well established heats of formation for N^+ and H to estimate the bond energy $D_0^0(\text{N-H}^+)$ which with the known ionization potentials of NH and H provided the dissociation energy $D_0^0(\text{NH}) = 3.40 \pm 0.03 \text{ eV}$. This accurate estimate falls between the experimental upper and lower limits and is consistent with the value recommended by Bauschlicher and Langhoff (1987).

The oscillator strength of a vibration-rotation line is given by

$$g_{N''} f_{N'N''}^{\nu\nu'} = 4.7015 \cdot 10^{-7} \sigma |D_{N'N''}^{\nu\nu'}|^2 S_{N'N''}, \quad (1)$$

where σ is the wavenumber of the transition in cm^{-1} and $g_{N''}$ is the statistical weight of the lower level. The rotational line intensity factors $S_{N'N''}$ were calculated from Kovacs’ (1969) expressions for triplet transitions. $D_{N'N''}^{\nu\nu'}$ is the vibration-rotation averaged transition dipole moment in Debye,

$$D_{N'N''}^{\nu\nu'} = \langle \Psi_{\nu'N'}(R) | D(R) | \Psi_{\nu N''}(R) \rangle, \quad (2)$$

where $D(R)$ is the electric dipole moment function of the NH ground state and $\Psi_{\nu N}(R)$ is the radial part of the vibration-rotation wave function. This wave function has been obtained by numerical integration of the radial nuclear eigenvalue equation, including the centrifugal term (see e.g. van Dishoeck and Dalgarno, 1983). The integration in Eq. (2) is over the internuclear distance R .

Elaborate theoretical calculations of the dipole moment function of the NH $X^3\Sigma^-$ state have been performed by Meyer and Rosmus (1975), Goldfield and Kirby (1987) and most recently Chackerian et al. (1989a). In contrast, little information is available from experiments. Scarl and Dalby (1974) have measured the permanent dipole moment of the $X^3\Sigma^- v=0$ state to be $1.389 \pm 0.075 D$. This value is significantly lower than the range $1.50\text{--}1.55 D$ found in the best theoretical calculations. Chackerian et al. (1989b) have very recently attempted to determine experimentally the transition moments for the lowest five fundamental bands of NH, using the Herman-Wallis effect. Their derived (absolute) value of the rotationless transition moment for the 1–0 band of $0.0648 \pm 0.008 D$ appears in reasonable agreement with the value of $0.0625 D$ computed by Meyer and Rosmus (1975) and that of $0.0594 D$ calculated by Chackerian et al. (1989a). However the experimental method assumes that the permanent dipole moment is known, and the value of $0.0648 D$ was obtained using the experimental dipole moment of Scarl and Dalby. Chackerian et al. (1989b) note that, if the theoretical values of the permanent dipole moment are adopted in the analysis, the experimental value for the 1–0 transition moment is increased by about 10%. Then, the experimental and theoretical values for the 1–0 transition moment appear to differ by more than their estimated uncertainties. In summary, the experimental and theoretical values for both the NH permanent dipole moment and the fundamental

Table 1. NH vibration-rotation lines

N ^p	Laboratory		Observed		A _N
	σ^1	$\bar{\sigma}$	σ	Equivalent width W _o (mK)	
<u>I-0 band</u>					
9	3374.795 .817 .846	.814	.80	0.72	2 8.09
10	3391.163 .181 .205	.181	.17	0.76	3 8.08
11	3405.840 .854 .874	.855	.83	0.85	2 8.10
13	3430.004 .010 .021	.013	.00	0.80	3 8.04
14	3439.434 .436 .444	.440	.43	0.81	3 8.03
16	3452.857 .851 .851	.856	.84	0.90	3 8.08
17	3456.800 .790 .786	.794	.785	0.73	2 8.00
18	3458.865 .852 .845	.854	.84	0.80	3 8.06

Table 1 (continued)

N ^p	Laboratory		σ	Observed		A _N
	σ^1	$\bar{\sigma}$		Equivalent width W _o (mK)	Weight ²	
19	3459.032 .015 .004	.017	.00	0.68	3	8.01
20	3457.221* .245* .277*	.243	.235	0.55	1	7.94
22	3447.817* .852* .896*	.841	.82	0.58	2	8.04
27	3389.073* .143* .224*	.147	.15	0.38	1	8.11
<u>2-1 band</u>						
7	3170.581 .607 .646	.598	.61	0.405	1	8.03
8	3188.962 .984 3189.017	.983	.99	0.432	1	8.00
9	3205.716 .734 .762	.740	.74	0.575	2	8.08

Table 1 (continued)

N ^p	Laboratory		σ	Observed		A _N
	σ^1	$\bar{\sigma}$		Equivalent width W _o (mK)	Weight ²	
11	3234.214 .222 .243	.235	.22	0.79	3	8.16
14	3263.966 .962 .972	.958	.94	0.603	3	8.00
15	3270.29* .27* .25*	.271	.27	0.75	3	8.09
16	3274.76* .74* .71*	.739	.74	0.54	2	7.95
17	3277.36* .33* .30*	.337	.35	0.73	1	8.09
18	3278.06* .02* 3277.98*	.02	.045	0.72	1	8.10
19	3276.84* .79* .74*	.79	.84	0.55	1	8.01
20	3273.66* .61* .55*	.67	.655	0.53	1	8.01

- (1) laboratory wavenumbers derived by Boudjaadar et al. (1986)
(2) a weight 1 to 3 is assigned to each line according to its appearance in the solar spectrum
(*) calculated from term energies

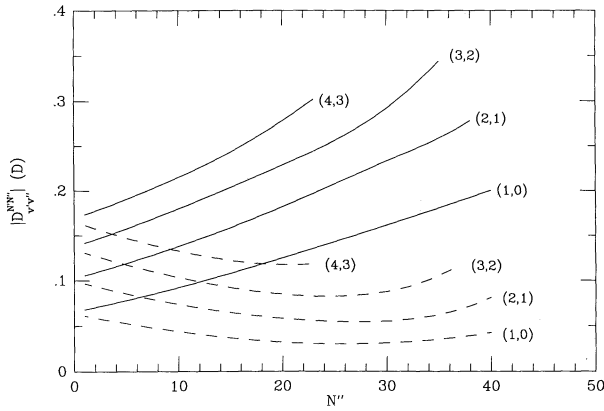


Fig. 2. The vibration-rotation transition matrix elements as function of lower rotational level N'' for the NH $X^3\Sigma^-$ (1,0)–(4,3) bands, obtained with the Meyer and Rosmus (1975) dipole moment function. Full lines: R -branch; dashed lines: P -branch

transition moments differ by about 10%. We note that the various theoretical determinations agree within a few percent. These factors suggest that the uncertainties in the oscillator strengths should not exceed 15%.

Matrix elements $D_{N''N'''}^{v'v''}$ for the NH $X^3\Sigma^-$ fundamental bands have been computed using both the Meyer and Rosmus (1975) and the Chackerian et al. (1989a) transition moment functions. An empirical RKR potential based on the constants of Boudjaadar et al. (1986) was employed up to the $v = 2$ turning points, and was extended to larger and smaller internuclear distances with the theoretical energies of Meyer and Rosmus. The results for the R and P lines in the 1–0 to 4–3 bands using the Meyer and Rosmus function are presented in Fig. 2. It is seen that the transition moments for the R lines are much larger than those for the P lines. Also, the R -branch matrix elements increase strongly with N'' , whereas those for the P -branch decrease slowly with N'' . For example, around $N'' = 15$ where the strongest solar lines occur, the individual R lines are calculated to be at least six times more intense than the individual P lines. So we can explain a posteriori the absence of all P lines, as noted earlier in the text.

Table 1 gives the abundance of nitrogen derived from each line of the two bands using the Meyer and Rosmus dipole moment function: from 12 lines of the 1–0 band and 11 lines of the 2–1 band we deduce a mean value of 8.052 ± 0.050 where the quoted uncertainty is the standard error of the mean. The two bands give consistent results: $A_N = 8.050 \pm 0.039$ (1–0) and 8.055 ± 0.066 (2–1). The scatter of the individual results about the means appears to receive its dominant contribution from the equivalent width measurements of these weak lines. If the Chackerian et al. (1989a) theoretical dipole moment function is used, the mean value is 8.09. If the Chackerian et al. (1989b) experimental transition moment for the 1–0 band is adopted, the abundance is lowered to about $A_N = 8.02$. A further reduction to $A_N = 7.95$ would occur if Chackerian et al.'s experimental results are adjusted to the theoretical permanent dipole moment. The lingering uncertainties in the NH dissociation energy and the dipole moment function introduce an overall uncertainty in the derived nitrogen abundance of about 0.03 and 0.06 dex respectively, where the 0.03 dex difference between the above abundances is partly a reflection of the latter uncertainty. In the light of these uncertainties, we recommend an abundance $A_N = 8.06 \pm 0.07$ where we give lower

weight to the experimental determination of the transition moments (Chackerian et al., 1989b).

3.2. The N I lines

Our value has to be compared with the value derived from the atomic (N I) lines. We revised and updated the analysis made by one of us (Lambert, 1978). All N I lines possibly present in the solar spectrum have been carefully measured and analyzed on the Jungfraujoch (Delbouille et al., 1973) and the Kitt Peak (Delbouille et al., 1981) solar atlases. These lines are faint and many of them are blended with CN lines. Their contribution to the N I lines has been calculated in the following way. The CN spectrum has been computed under solar conditions and then fitted to observed lines of the same bands. The CN contributions estimated in that way, and subtracted from the total equivalent width of the N I features whenever necessary, are accurate to within 5%. We finally retained 23 N I lines belonging to the $3s-3p$, $3p-3d$ and $3s'-3p'$ transitions which are displayed in Table 2. We estimate the accuracy of the equivalent widths of these faint N I lines to be no better than 10 to 20%.

Lambert (1978) summarized the then available data on the transition probabilities. Very recently however, the situation concerning the N I transitions of solar interest has evolved quite a lot: refined theoretical techniques (including configuration interaction to various degree) have been used by Biémont et al. (1989), Suskin and Weiss (1989) and Lennon (1989), to which we shall add Aashamar et al. (1983). They computed transition probabilities for some of our $3s-3p$ lines and 3 lines of the $3p-3d$ transitions (Biémont et al.), for the transitions between quartets in $3s-3p$ (Suskin and Weiss), for the $3s-3p$ transitions (Lennon) and for all of our transitions (Aashamar et al.). Only Biémont et al. (1989) included fine structure. For the other data, we derived the line f -values from the computed multiplet f -values using LS-coupling relative intensities within multiplets, a reasonable assumption from the results of Richter (1961), Biémont et al. (1989), and Zhu et al. (1989).

Zhu et al. (1989) recently measured the relative transition probabilities of most of the $3s-3p$ transitions of Table 2 (except for 8683.4 and 9392.8). These very accurate data were then normalized to an absolute scale utilizing accurate lifetime results for the $3p^4S_{3/2}^0$ and $3p^4D^0$ levels. The uncertainty of these absolute transition probabilities is of $\pm 12\%$ (± 0.05 dex).

Comparison of all the available gf -values for the $3s-3p$ transitions [we also considered Richter's (1961) experimental values and theoretical values obtained by Kurucz and Peytremann (1975) and by using the Coulomb approximation (CA)] shows that the recent experimental values of Zhu et al. (1989) are in perfect agreement with the theoretical values of Biémont et al. (1989): $\Delta \log gf$ (exp.–theor.) = -0.001 ± 0.016 dex. We shall therefore adopt, as our “best values” for these $3s-3p$ transitions, the mean f -values between Zhu et al. and Biémont et al. For the lines not considered in both works we adopt either the experimental result when available or the theoretical one.

The other sets of gf -values for the $3s-3p$ transitions differ noticeably from these “best values”: $\Delta \log gf$ (author–best) = 0.068 ± 0.028 dex (Aashamar et al., 1983), 0.050 ± 0.019 (Suskin and Weiss, 1989), -0.122 ± 0.039 (Lennon, 1989), 0.046 ± 0.030 (CA), and 0.067 ± 0.027 (Kurucz and Peytremann, 1975). These differences are valid for quartets. For doublets the differences are much smaller (~ -0.02 dex). For Richter's (1961) experimental values, we find $\Delta \log gf = -0.075 \pm 0.034$ dex, with no difference between quartets and doublets as expected.

Table 2. Ni I lines in the solar spectrum

Transition E_{exc}^{low}	$\lambda(\text{\AA})$	$W_{\lambda}^{tot}(\text{m\AA})$	W_{λ} (CN)	W_{λ} (N I)	log gf	A_N	Weight
<u>3s-3p</u>							
$4P - 4S^0$	7468.309	5.2	-	5.2	-0.208 ¹	8.07	2
(10.34eV)	7442.299	3.3	0.7	2.6	-0.411 ¹	7.91	1
$4P - 4P^0$	8216.345	8.6	-	8.6	-0.106 ¹	8.03	2
(10.34eV)	8200.363	1.3	0.15	1.15	-0.996 ²	8.14	1
	8242.393	4.2	0.3	3.9	-0.260 ²	7.97	1
	8223.140	2.4	-	2.4	-0.288 ²	7.76	1
$4P - 4D^0$	8683.401	8.7	0.9	7.8	0.109 ³	7.90	2
(10.34eV)	8718.826	5.1	0.9	4.2	-0.344 ¹	8.04	1
$2P - 2P^0$	8629.238	6.35	1.85	4.5	0.082 ¹	7.91	1
(10.69eV)	8655.869	1.5	0.1	1.4	-0.608 ¹	8.06	1
$2P - 2D^0$	9392.789	11.6	1.9	9.7	0.354 ³	8.02	2
(10.69eV)							
<u>3p-3d</u>							
$4D^0 - 4F$	10114.644	5.5	-	5.5	0.766 ³	8.08	1
(11.76eV)	10112.483	3.5	-	3.5	0.611 ³	8.01	1
	10108.893	3.15	0.65	2.5	0.431 ³	8.02	1
	10105.130	1.8	-	1.8	0.220 ³	8.08	1
$4P^0 - 4D$	10539.573	3.2	-	3.2	0.529 ⁴	8.07	1
(11.84eV)	10507.004	1.4	-	1.4	0.249 ⁴	7.97	1
	10520.583	0.8	-	0.8	-0.045 ⁴	8.01	1
$4P^0 - 4P$	10757.888	0.8	-	0.8	-0.098 ⁴	8.04	1
(11.84eV)							
$4S^0 - 4P$	12381.650	2.25	0.9	1.35	0.284 ⁵	7.83	1
(12.00eV)							
$2D^0 - 2F$	12469.620	5.5	0.5	5.0	0.622 ⁵	8.10	1
(12.00eV)	12461.250	2.6	-	2.6	0.463 ⁵	7.94	1
<u>3s'-3p'</u>							
$2D - 2F^0$	9045.878	0.8	-	0.8	0.430 ⁶	8.03	1
(12.36eV)							

(1) Mean of Zhu et al. (1989) and Biémont et al. (1989) ; see text

(2) Zhu et al. (1989) ; see text

(3) Biémont et al. (1989) ; see text

(4) Mean of Aashamar et al. (1983) and Richter (1961) scaled to Biémont et al. (1989) ; see

text

(5) Aashamar et al. (1983) scaled to Biémont et al. (1989) ; see text

(6) Mean of Aashamar et al. (1983) and Richter (1961) ; see text

The situation is much less clear for the $3p-3d$ transitions. Hopefully, Biémont et al. (1989) computed f -values for the $4D^0-4F$ lines (the 10105.1 line is not given by these authors; we derived the gf -value from their data for the three other lines given in Table 2 and LS-coupling relative intensities, the new theoretical results being in good agreement with LS-coupling). In agreement with the results from $3s-3p$ transitions, Biémont et al. (1989) results will be our "best values" for the $4D^0-4F$ transitions.

Comparison of all the available gf -values for the $3p-3d$ transitions with those of Biémont et al. for the $4D^0-4F$ line shows that $\Delta \log gf$ (author-best) = -0.065 ± 0.006 dex (Aashamar et al., 1983), 0.006 ± 0.006 (Richter, 1961), -0.032 ± 0.006 (CA), and -0.049 ± 0.060 (Kurucz and Peytremann (1975)). If we "normalize", by the hereabove mentioned amounts, the results by these different authors for the remaining lines of the $3p-3d$ transitions (not given by Biémont et al.), we see that the new

Aashamar et al. scaled f -values agree to within 0.025 dex with Richter's scaled f -values (the differences in Richter's data between $3s-3p$ and $3p-3d$ transitions probably reflect problems of calibration of the intensities versus wavelength). Our "best values" for these remaining lines of the $3p-3d$ transitions will then be means between Aashamar et al. (1983) scaled gf -values and Richter's (1961) scaled gf -values for $4P^0-4D$ and $4P^0-4P$ lines and Aashamar et al. scaled for $4P^0-4P$ and $2D^0-2F$ (Richter has not measured these lines).

For the $3s'-3p'$ transition no new value exists but Aashamar et al. (1983), Richter (1961), Kurucz and Peytremann (1975) and CA agree to within 0.03 dex. We shall adopt the mean between Aashamar et al. and Richter.

The abundance results derived from 23 Ni I lines using the gf -values discussed hereabove are given in Table 2. The mean result is $A_N = 8.00 \pm 0.09$; the individual results do not show any

dependence against the excitation energy of the lower level. It is in very good agreement with the value obtained by Biémont et al. (1989) from a more restricted sample of lines (12): $A_N = 7.99 \pm 0.05$. Our result derived from 23 N I lines, $A_N = 8.00 \pm 0.09$ is not significantly different from the result obtained from 23 vibration-rotation lines of NH, $A_N = 8.06 \pm 0.07$.

4. Conclusions

This study has permitted us to identify for the first time vibration-rotation lines of NH in the solar infrared spectrum near $\lambda 3 \mu\text{m}$. More than thirty of these lines belonging to the 1–0, 2–1 and 3–2 bands have been measured with great accuracy: the observed equivalent widths lead to a solar abundance of nitrogen of 8.06 ± 0.07 adopting $D_0^0(\text{NH}) = 3.37 \text{ eV}$ from recent theoretical determination and the electric dipole moment function calculated by Meyer and Rosmus (1975) and Chackerian et al. (1989a). Our final recommended abundance $A_N = 8.03 \pm 0.07$ gives the same weight to the NH and N I results. This value is 0.04 dex larger than the value recommended by one of us (Lambert, 1978), essentially based on the N I $3s-3p$ lines together with the gf -values available at that time.

As atomic and molecular lines will react in opposite ways to temperature modifications, the rather good agreement between the atomic (N I) and molecular (NH) results is an argument in favour of the photospheric model used. Furthermore, the recommended nitrogen abundance should be somewhat insensitive to temperature modifications.

The problem with the N I lines shows once more the need for high precision atomic data in solar spectroscopy. Accurate gf -values are urgently needed for some of the N I $3p-3d$ lines of solar interest.

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Note added in proof: Recently, W.R. Anderson (*J. Phys. Chem.* **93**, 539, 1989) remeasured very accurately the dissociation energy of NH: $D_0^0 = 3.42 \pm 0.01 \text{ eV}$. A new elaborate calculation of the electric dipole moment function of NH has very recently been made by E. Cantarella, F. Culot, and J. Liévin (Université Libre de Bruxelles; private communication): it is in very good agreement with the EDMF of Meyer and Rosmus (1975) adopted in this analysis. Taking these new molecular data into account reduces the recommended solar abundance of nitrogen to $A_N = 8.00 \pm 0.05$.

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