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Vibration-rotation bands of CH in the solar infrared spectrum and the solar carbon 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 identify and measure a large number of lines of the vibration-rotation fundamental bands of the $X^2\Pi$ state of CH. From about 100 lines of the 1–0, 2–1, and 3–2 bands and adopting theoretical transition probabilities, we derive a solar carbon abundance $A_C = 8.60 \pm 0.05$. This value is compared with new results inferred from other carbon abundance indicators, such as the C_2 Swan and Phillips bands, the CH $A^2\Delta - X^2\Pi$ transition, and the C I lines. Our final recommended solar abundance of carbon is $A_C = 8.60 \pm 0.05$.

Key words: abundances: solar – atomic and molecular data – solar spectrum

1. Introduction

It is well known that the CH radical plays an important role in many astronomical sources: late type stars (especially carbon stars), comets, interstellar matter, ... In the solar visible spectrum, the three electronic systems of CH (*A–X*, *B–X*, *C–X*) have been known for quite some time (Moore et al. 1966). Only recently have the infrared vibration-rotation lines of the $X^2\Pi$-state been detected in the solar photospheric spectrum (Sauval & Grevesse 1985) using the first experimental study of these transitions by Lubic & Amano (1984; 1–0 band; N'', rotational quantum number, $\leqq 8$).

A tentative identification of lines of the fundamental band of CH in the spectrum of a carbon star, TX Psc, was reported by Ridgway et al. (1977) and confirmed by Ridgway et al. (1984). Lambert et al. (1986) identified these transitions in several other carbon stars. All these identifications were based on predicted frequencies derived from the term values obtained from the analysis of the electronic bands.

From the laboratory analyses of Lubic & Amano (1984) and Bernath (1987; 1–0, 2–1, 3–2 bands but still for rather low N''-values, $N'' \sim 9$) and many other unsuccessful trials, it is clear that it is very difficult to obtain "hot" CH in laboratory sources. The best source for producing the vibration-rotation spectrum of CH has been proven to be the Sun!

New high resolution, low noise solar spectra obtained from space by the ATMOS experiment (Farmer & Norton 1989) have permitted us to extend the identification of the CH vibration-rotation lines to much higher N''-values than in the laboratory, and even to higher vibrational levels, with the 4–3 band being detected for the first time. Although these solar lines are weak, the solar infrared spectrum is cleaner than that of a carbon star (Lambert et al. 1986), at high resolution and high signal-to-noise ratio.

A total of 558 vibration-rotation lines of CH has been observed in the solar infrared spectrum (2500–3040 cm^{-1}). The equivalent widths of these lines have been carefully measured and about 1/5 of these lines are used to derive an accurate value of the solar carbon abundance.

An accurate knowledge of the solar C, N, and O abundances is crucial in many areas of astronomy, ranging from depletion studies in the interstellar medium to the determination of the composition of planets and their atmospheres (Lambert 1978). Of the three elements, the abundance of carbon is the most poorly determined. The high quality CH data presented in this paper significantly reduce the uncertainties in this value. We also derive the solar carbon abundance from other indicators such as the C_2 Swan and Phillips bands, the CH *A–X* transition, and the C I and [C I] atomic lines. These results are compared with the value obtained from the analysis of the CH vibration-rotation lines.

2. Laboratory and solar vibration-rotation spectra of CH

Based on Bernath's (1987) line positions, we easily detected the low N'' CH lines on high resolution (0.01 cm^{-1}), low-noise solar spectra obtained by the ATMOS (Atmospheric Trace Molecule Spectroscopy) Fourier transform spectrometer experiment on board the Space Shuttle (Spacelab 3 flight, April 29–May 6, 1985). These first observations of a pure (i.e. not contaminated by telluric absorption) solar spectrum in the infrared (600–4000 cm^{-1}; Farmer & Norton, 1989) have been obtained from a small circular region near the solar disk center ($\cos\theta = 0.935$). Extension of the identifications to higher N''-values, beyond the

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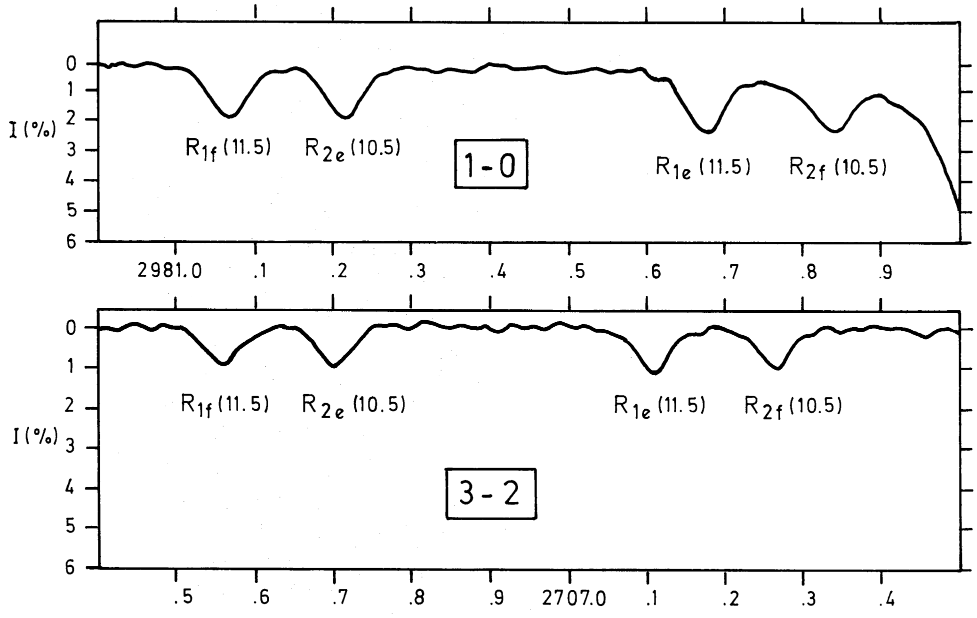

Fig. 1. Solar spectrum around the $R(11)$ lines of the 1–0 vibration-rotation band and the $R(11)$ lines of the 3–2 vibration-rotation band of CH

limit of the laboratory measurements, has been made carefully. We have thus been able to follow the R-branches up to $N''=34$ for the 1–0 and 2–1 bands and up to $N''=31$ for the 3–2 band. For comparison the highest value measured by Bernath is $N''=9$. Many lines of the 4–3 band (R-branch), up to $N''=24$, have also been identified without ambiguity. The solar lines, most of them detected for the first time, have been used to derive a new set of accurate molecular constants for the $X^2\Pi$ state of CH (Mélen et al. 1989).

We measured the equivalent widths (W_σ) of about 100 CH lines in the R-branches (see Sect. 3). The other lines are either too strongly blended or too weak to allow their W_σ to be measured with accuracy. Note that the strongest of these CH vibration-rotation lines have equivalent widths of the order of 1 mK and central depths of about 2%. Figure 1 shows an enlargement of the solar spectrum around the $R(11)$ lines of the 1–0 and 3–2 bands.

Goldman et al. (1981) suggested that pure rotation lines of CH ($X^2\Pi$) might possibly be present in the solar infrared spectrum. In the absence of any laboratory data, we predicted the positions of these lines from the molecular constants of Mélen et al. (1989) and we unsuccessfully searched for these lines in our solar spectra from 600 to 1100 cm^{-1}. We then computed vibration-rotation averaged dipole moments from the dipole moment function of Follmeg et al. (1987) and we predicted that the strongest pure rotation lines of CH should be about 25 times fainter than the corresponding lines of OH that are present in the same spectral region (Sauval et al. 1984). This clearly explains the absence of the pure rotation lines of CH.

On the other hand, CH has a low-lying electronic state, the $a^4\Sigma^-$ state, about 0.7 eV above the ground $X^2\Pi$ state. In the solar atmosphere, this state is expected to contain about 20% of the CH molecules, so that vibration-rotation lines within this state may be measurable as well. Spectroscopic constants for pure rotational transitions in $v=0$ have been reported by Nelis et al. (1990), but no laboratory frequencies are yet available for the vibration-rotation lines. The dipole moment function for the $a^4\Sigma^-$ state has been computed by Follmeg et al. (1987), and the resulting averaged dipole moments for the fundamental bands are typically a factor of two below those for bands in the $X^2\Pi$ state. For these reasons, we expect the vibration-rotation lines within the $a^4\Sigma^-$ state to be of the order of ten times fainter than the corresponding solar lines in the $X^2\Pi$ state. Once the spectroscopic properties are better known, searches for these lines would be valuable on high quality solar spectra, and also in spectra of carbon stars.

3. Solar analysis

Line profiles and equivalent widths of all the CH lines have been calculated using a solar atmosphere model and basic molecular data such as the dissociation energy of CH and transition probabilities. For each line, the carbon abundance is adjusted to match the observed equivalent width.

Our solar model, that was used in our recent analysis of NH (Grevesse et al. 1990), is very similar to Holweger & Müller's (1974) model. The influence of the microturbulent velocity on the weak CH lines is negligible; a value of 0.9 km s^{-1} has been adopted (Simmons & Blackwell 1982; Blackwell et al. 1984). Local thermodynamic equilibrium (LTE) is assumed throughout our analysis of CH and other lines.

The dissociation energy of CH is known accurately: $D_0^0=3.465\pm0.010$ eV (Huber & Herzberg 1979). Partition functions and equilibrium constants have been taken from Sauval & Tatum (1984).

The oscillator strengths for the CH vibration-rotation lines have been derived in the same manner as for NH and OH (see Grevesse et al. 1990; Eqs. (1) and (2)). Since the ground state is of $^2\Pi$ character, spin-orbit coupling leads to a spectrum with six main branches ($P_1, P_2, Q_1, Q_2, R_1, R_2$), each of which consists of two lambda-doubling components e and f. The rotational line intensity factors $S_{N'N''}$ for these lines were calculated from the formulae given by Bennett (1970). The $S_{N'N''}$ values for the R and P lines are similar in magnitude, but are very small for the Q lines. We assume that both spin-orbit interaction and lambda doubling can be neglected in the calculation of the transition matrix elements; Mies (1974) has shown that such effects are small (about 1–2% change) for the case of OH (also $X^2\Pi$). Thus, the computed oscillator strengths have the same value for the four lines corresponding to each N'' (e.g. R_{1e}, R_{1f}, R_{2e}, R_{2f}).

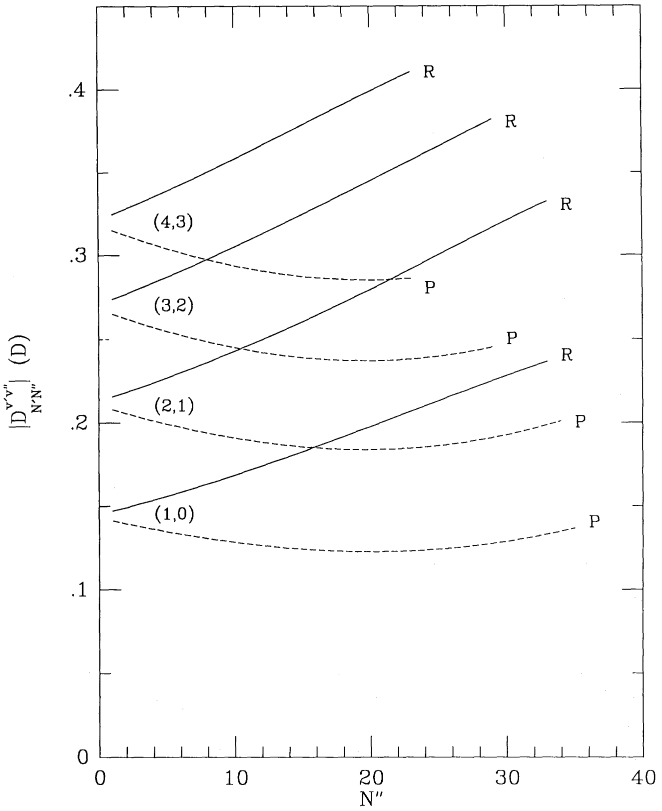

Fig. 2. The vibration-rotation matrix elements for the CH($X^2\Pi$) 1–0 to 4–3 bands, as a function of the lower rotational level N'', obtained with the Follmeg et al. (1987) dipole moment function; the matrix elements for the Q-branches lie in between those for the R- and P-branches

Theoretical calculations of the CH $X^2\Pi$ electric dipole moment as a function of internuclear separation have been performed by Lie et al. (1973), Meyer & Rosmus (1975), and most recently by Follmeg et al. (1987). Vibration-rotation averaged transition dipole moments $D^{v'v''}_{N'N''}$ have been computed using Bernath's (1987) empirical RKR potential, extended to larger and smaller internuclear distances with the theoretical energies of Follmeg et al. (1987). The matrix elements obtained using the Follmeg et al. dipole moment function, which is based on a very elaborate calculation, differ by less than 10% from those obtained using the older functions. This suggests that, in contrast to the case for OH, the CH results are not very sensitive to the details of the calculation. This results mostly from the fact that the CH dipole moment function peaks at a distance $R = 1.3$ bohr, which is much smaller than the ground state equilibrium distance $R_{\rm eq} = 2.12$ bohr. The intensities of the fundamental bands are sensitive to the slope of the dipole moment function around $R_{\rm eq}$. Thus, for the case of CH, they sample the part of the function where it decreases nearly linearly. In contrast, the OH dipole moment function peaks close to $R_{\rm eq}$, so that its slope is varying rapidly in the region of interest. No experimental determinations of the strengths of the CH fundamental bands exist, but the CH permanent dipole moment has been measured to be 1.46 ± 0.06 D (Phelps & Dalby 1966). The permanent dipole moment for $N'' = 1$ using the Follmeg et al. dipole moment function is somewhat lower, 1.36 D. We estimate the total uncertainties in the adopted oscillator strengths based on the Follmeg et al. dipole moment function to be of order 10%.

Figure 2 shows the matrix elements $D^{v'v''}_{N'N''}$ as functions of N'' for the R- and P-branches. The matrix elements for lines in the Q-branches lie between the R- and P-branch results but because of their low $S_{N'N''}$ values, the Q-branch lines are too weak to be observed. It is readily seen from Fig. 2 that the R-branch lines will be much stronger than the P-branch lines for high N'', since they have similar rotational line strength factors.

4. The solar carbon abundance

In this section, we will first derive the solar carbon abundance from the observed vibration-rotation lines of CH and then compare the result with values obtained from a new analysis of other indicators of the carbon abundance.

4.1. The CH vibration-rotation lines

The abundances derived from 104 lines within the R-branches of the 1–0, 2–1 and 3–2 bands are plotted in Fig. 3 as functions of the excitation energy of the lower levels. No dependence on excitation energy is found, and no significant difference occurs between the three bands.

The mean carbon abundance derived from these 104 lines of CH is $A_{\rm C} = 8.601 \pm 0.034$. The dispersion is only slightly larger than that attributable to the measurement errors of the equivalent widths. Because the uncertainties in the adopted oscillator strengths are estimated to be about 10%, the recommended carbon abundance based on the vibration-rotation lines of CH is $A_{\rm C} = 8.60 \pm 0.05$.

4.2. The C_2 Swan system

The carbon abundance can also be derived from observations of the C_2 molecule. The C_2 $d^3\Pi_g$–$a^3\Pi_u$ Swan system has previously been analyzed by Grevesse & Sauval (1973) and by Lambert (1978). Note that there is an error of a factor of two in the solar band oscillator strength, $f^{\odot}_{00}$, derived by Grevesse & Sauval: $f^{\odot}_{00} = 2.8\ 10^{-2}$ instead of $1.4\ 10^{-2}$. A sample of 20 high quality lines of the (0,0) band has been chosen from the Jungfraujoch solar atlas (Delbouille et al. 1973). Computations of the solar carbon abundance were made using the model used for the CH vibration-rotation lines.

The C_2 Swan band oscillator strengths are well determined from measurements of the $d^3\Pi_g$ state's radiative lifetime. Although early measurements of the lifetime of the $v = 0$ level of the $d^3\Pi_g$ state seemed to indicate $\tau_0 \approx 120$ ns (see Erman 1980 and references therein), more recent measurements of Stark & Davis (1985), Bauer et al. (1986), Naulin et al. (1988) and Bergström et al. (1989) appear to converge to a value that is about 20% lower: 92 ± 5, 106 ± 15, 101.8 ± 4.2, and 100 ± 10 ns, respectively. Theoretical calculations also favor the lower values: if the dipole moment function of Chabalowski et al. (1981) is combined with a RKR potential, $\tau_0 = 93$ ns is obtained, corresponding to $f_{00} = 3.21\ 10^{-2}$. The dipole moment function of Klotz (1987) results in $\tau = 98$ ns, or $f_{00} = 3.03\ 10^{-2}$ (Gredel et al. 1989). We will adopt a weighted mean of the lower experimental and theoretical results: $\tau_0 = 98 \pm 5$ ns, corresponding to $f_{00} = 3.03\ 10^{-2}$. Note that strictly speaking the lifetime measurements give an upper limit to the oscillator strength for the Swan band system, since the $d^3\Pi_g$ state can also decay radiatively to the $c^3\Sigma_u^+$ state. However, calculations by Klotz (1987) of the $d^3\Pi_g$–$c^3\Sigma_u^+$ transition dipole moment suggest that this transition contributes only 2% of the total decay rate of the d state.

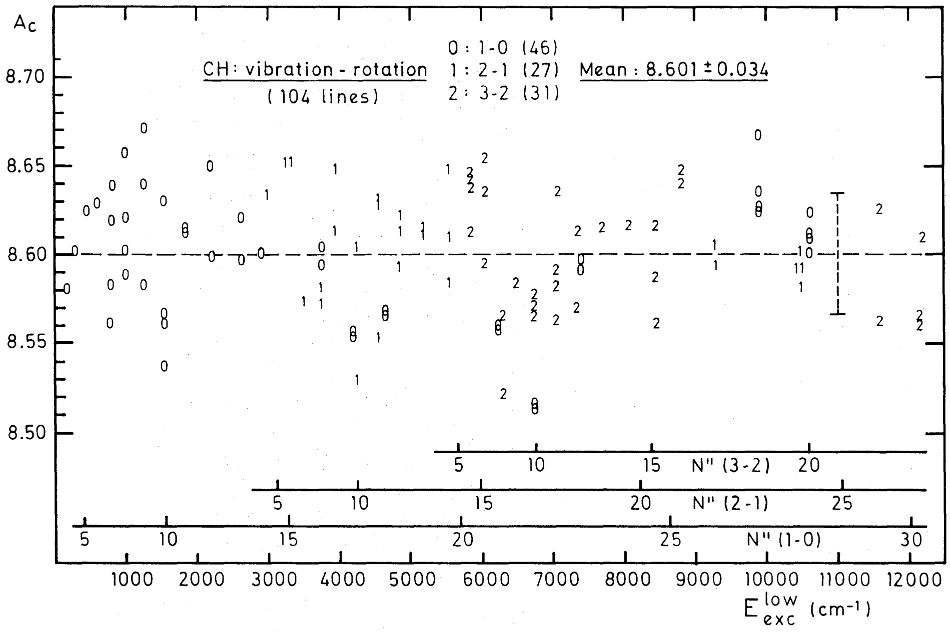

Fig. 3. Solar abundance of C versus the excitation energy of the lower level of the transition as derived from the CH vibration-rotation lines present in the infrared solar spectrum

The principal uncertainty in the analysis is the dissociation energy of C_2. Huber & Herzberg (1979) recommend $D_0^0 = 6.21$ eV, but Lambert (1978) adopted a lower value: $D_0^0 = 6.11 \pm 0.04$ eV. Huber & Herzberg base their recommendation on two thermochemical values: $D_0^0 = 6.25 \pm 0.2$ eV (Brewer et al. 1962) and $D_0^0 = 6.17 \pm 0.11$ eV (Kordes & Gingerich 1973). It seems clear that an uncertainty of ± 0.1 eV should be attached to the recommended value of $D_0^0 = 6.21$ eV. Lambert's lower D_0^0 is the spectroscopic value (rotational predissociation of $C^1\Pi_g$) given by Messerle & Krauss (1967). Ab initio calculations lead Bauschlicher et al. (1988) to conclude that the dissociation energy is around $D_0^0 = 6.17$ eV with ± 0.05 eV as, perhaps, an estimated uncertainty.

If $D_0^0 = 6.21$ eV is used, we find $A_C = 8.61 \pm 0.03$ from 20 high-quality lines of the Swan band, whereas $A_C = 8.66 \pm 0.03$ if $D_0^0 = 6.11$ eV is adopted. The carbon abundance scales with the molecular parameters through the relation

$$\Delta A_C(\text{dex}) \approx \mp \frac{\Delta \log f_{00}}{2} \mp \frac{\Delta D_0^0((\text{eV}))}{2}.$$

Thus, the carbon adundance derived from the C_2 Swan band observations is consistent with that found from the CH vibration-rotation lines if the C_2 dissociation energy is at least 6.21 eV.

4.3. The C_2 Phillips bands

Solar lines of C_2 can be observed in the Phillips bands, $A^1\Pi_u - X^1\Sigma_g^+$. We update here the analysis made previously by two of us for the 0–0 and 1–0 bands (Brault et al. 1982). The C_2 Phillips lines are very faint, and have been very carefully measured on the Kitt Peak solar atlas (Delbouille et al. 1981). After reanalysis of the line profiles, we rejected about half the lines selected by Brault et al. If we apply to the 20 Phillips lines the criteria applied to the C_2 Swan band lines or the CH vibration-rotation lines, all 20 lines would have the lowest weight.

The uncertain parameters in the derivation of the solar carbon abundance from the Phillips bands are again the C_2 dissociation energy, and the oscillator strengths for the lines. For the dissociation energy, we adopt $D_0^0(C_2) = 6.21$ eV, as inferred from the C_2 Swan band results. The Phillips system oscillator strengths have been the subject of considerable discussion in recent years. The latest experimental results, inferred from Bauer et al.'s (1986) lifetimes, favor $f_{00} = (1.5 \pm 0.25)\ 10^{-3}$ and $f_{10} = (1.6 \pm 0.25)\ 10^{-3}$, whereas the analysis of Davis et al. (1984) of the Phillips/Swan band ratios leads to $f_{00} = 1.68\ 10^{-3}$ and $f_{10} = 2.06\ 10^{-3}$, if $f_{00} = 3.03\ 10^{-2}$ is adopted for the Swan (0,0) band. The early theoretical results (van Dishoeck 1983; Chabalowski et al. 1983) were typically a factor of two larger than these experimental results, and subsequent more extensive calculations (O'Neil et al. 1987; Klotz 1987) found values that were about 50% larger than experiment. Langhoff et al. (1990) have performed very accurate calculations of the C_2 Phillips band transition moment function, and investigated systematically the sensitivity of the results to the computational procedure. Their resulting oscillator strengths of $f_{00} = 2.28\ 10^{-3}$ and $f_{10} = 2.38\ 10^{-3}$ are claimed to be accurate to about 5%, but are still substantially larger than the experimental values.

If the experimental oscillator strengths of Bauer et al. are adopted, together with $D_0^0 = 6.21$ eV, the inferred carbon abundance is $A_C = 8.67 \pm 0.05$, considerably larger than the carbon abundance derived from the CH vibration-rotation lines and the C_2 Swan bands. On the other hand, if the theoretical values of Langhoff et al. are adopted, we find $A_C = 8.58 \pm 0.05$ for both the 0–0 and 1–0 bands, consistent with the other analyses.

Because of the uncertainties in the solar equivalent widths and the continuing discrepancies between the theoretical and experimental oscillator strengths, we do not consider the C_2 Phillips band to be a good indicator of the solar carbon abundance. Nevertheless, the solar data form a good test of the transition probabilities and indicate that the recent theoretical results by Langhoff et al. are to be preferred.

4.4. The CH electronic transition $(A-X)$

The lifetime of the $v' = 0$ state and therefore the transition probability of the 0–0 transition is well known, because the Franck-Condon factor is very near to unity. The best experimental value is $\tau = 526 \pm 11$ ns (Bauer et al. 1989). The best theoretical value (Larsson & Siegbahn 1983, 1986) is in excellent agreement with this result, $\tau = 525$ ns. This radiative lifetime corresponds to $f_{00} = (5.16 \pm 0.11)\ 10^{-3}$.

Predissociation ensures that the experimental lifetimes of the $v' = 1$ and $v' = 2$ are equal to or shorter than the radiative lifetimes (see a summary by Ortiz & Campos 1982). For the lines of the 1–1 band, we shall thus use the theoretical prediction of Larsson & Siegbahn (1983, 1986), normalized to the experimental lifetime for $v' = 0$: $f_{11} = 4.46\ 10^{-3}$ which corresponds to $\tau_1 = 592$ ns.

We updated previous studies concerning the CH A–X system (Grevesse & Sauval 1973; Lambert 1968, 1978; Chmielewski 1984). We kept only the best lines in the list of Grevesse & Sauval: 6 lines of the 0–0 band and 3 lines of the 1–1 band were remeasured on the Jungfraujoch solar atlas (Delbouille et al. 1973).

From these 9 lines we find $A_\mathrm{C} = 8.60 \pm 0.04$, in good agreement with the result obtained from the vibration-rotation lines. Nevertheless because we had to disregard most of the numerous CH A–X lines that are difficult to measure with accuracy in the solar spectrum, we shall not consider this system as a good indicator of the solar abundance of carbon.

4.5. *The* C I *lines*

We revised and updated the analysis made by one of us (Lambert 1978). All C I lines present in the solar photospheric spectrum have been carefully measured and analyzed on the Jungfraujoch (Delbouille et al. 1973) and Kitt Peak (Delbouille et al. 1981) solar atlases. We finally retained the faintest lines belonging to the $3s$–$3p$, $3s$–$4p$, $3p$–$3d$ and $3p$–$4s$ transition arrays; they are listed in Table 1. The strongest lines of the $3s$–$3p$ transition array cannot be considered as good abundance indicators because of their strong dependence on the damping parameter.

For the $3s$–$3p$, $3p-3d$ and $3p$–$4s$ transitions arrays, we adopted the theoretical transition probabilities of Nussbaumer & Storey (1984; NS) and of Luo & Pradhan (1989; OP; calculations for the Opacity Project; Seaton 1987). These two sets of transition probabilities, which generally agree to within a few percent, are in good agreement with recent lifetime measurements of the $3p\,^3D$ and $3p\,^3P$ levels (Bergström et al. 1989) and the experimental oscillator strengths of Goldbach & Nollez (1987) and of Goldbach et al. (1989) for ultraviolet lines.

For three lines, however ($3p$–$4s$, $^1P_1$–$^1P_1^0$, $\lambda 10541.2$; $3p$–$3d$, $^1D_2$–$^1P_1^0$, $\lambda 16333.9$ and $^1S_0$–$^1P_1^0$, $\lambda 21023.2$), the NS and OP f-values disagree by rather large amounts: log OP/NS = 0.323, −0.416, and 0.120 dex respectively. The solar abundance results ($\lambda 16333.3$ is difficult to measure; $W_\lambda \cong 20.0$ mÅ) show that the OP gf-values are to be preferred to the NS values. In each case, the abundances obtained using the OP gf-values (8.53, 8.61, and 8.61 respectively) agree with the mean abundance derived from all the other lines, $A_\mathrm{C} = 8.59$, whereas the use of the NS gf-values leads to abundances of 8.85, 8.19, and 8.73, respectively, that differ significantly from this mean.

The breakdown of LS-coupling has already been discussed by one of us (Lambert 1968). Intermediate coupling (IC) calculations of NS confirm that there are significant differences between LS and IC results for some multiplets. Solar abundance results derived using gf-values from NS and OP, together with LS-coupling relative line strengths show dispersions about twice as large as when the same gf-values for multiplets are used together with IC relative line strengths from NS. Therefore, our "best" gf-values, for $3s$–$3p$, $3p$–$3d$ and $3p$–$4s$ transitions, are given by the average of NS and OP predictions for the multiplets gf-values with IC relative line strengths from NS, with the exception of the 3 lines mentioned above.

We had to disregard lines of the ^3D–$^3F^0(3p$–$3d)$ and ^3P–$^3P^0(3p$–$4s)$ multiplets. Although the NS and OP gf-values agree for these multiplets, the solar abundances are significantly smaller than the mean abundance deduced from other lines (see Table 1). Other lines of these multiplets, not retained in Table 1 because they are blended in the solar spectrum, confirm this discrepancy. We thus suspect the gf-values of the multiplets are too large.

The three lines of the $3s$–$4p$ transition array that have been used in previous studies of the solar carbon abundance also lead to a problem. Jones & Wiese (1984) measured accurate (±5%) relative transition probabilities for these lines which they normalized to an absolute scale using the absolute transition probability of Stuck & Wende (1974) for the $\lambda 5052.2$ ($^1P_1^0$–$^1D_2$) line. Using these gf-values we find $A_\mathrm{C} = 8.78 \pm 0.05$, a value much larger than the mean result derived from other lines (see Table 1). Nussbaumer & Storey (1984) do not give gf-values for these transitions and the theoretical results of Luo & Pradhan (1989) disagree both on an absolute and relative scale with Jones and Wiese's experimental data.

Comparison of the results of Stuck & Wende (1974) with the transition probabilities of Goldbach & Nollez (1989), Goldbach et al. (1989), Nussbaumer & Storey (1984), and Luo & Pradhan (1989) for several ultraviolet lines clearly shows no disagreements in the gf-values for strong lines ($\log gf \sim 0.0$), but Stuck & Wende's values are obviously too small by 0.15 to 0.25 dex for faint lines ($\log gf \leqq -0.5$). This suggests that Stuck & Wende's $\log gf$-value for $\lambda 5052.2$ (also a faint line) is too small by 0.20 ± 0.05 dex i.e. $\log gf$ (5052.2) corrected $= -1.57 + 0.20 = -1.37\,(\pm 0.10)$. A comparison of Richter (1958)'s experimental results for $3s$–$3p$, $3p$–$3d$ and $3p$–$4s$ transitions with the theoretical results of NS and OP gives $\log(\overline{gf}(\mathrm{OP, NS})/gf(\mathrm{R})) = 0.16 \pm 0.03$, with a surprisingly small dispersion when one recalls that Richter's experimental results have accuracies of the order of 0.04 to 0.06 dex. Applying this correction to Richter's original value for $\lambda 5052.2$ leads to $\log gf\ (5052.2) = -1.44(\pm 0.10)$, in good agreement with the value −1.37 above. We shall thus adopt a "best" value for $\log gf(5052.2) = -1.40 \pm 0.12$. For the other two lines of the $3s$–$3p$ transition array, $\lambda 4775.4$ and $\lambda 5380.3$, we adopt the relative values of Jones & Wiese (1984) normalized to our best value for $\lambda 5052.2$. Using these $\log gf$-values for the three lines, we find $A_\mathrm{C} = 8.63 \pm 0.06$, instead of $A_\mathrm{C} = 8.78$, a value which agrees with the result derived from the other transition arrays. If we use the OP gf-values from Luo & Pradhan (1989), we find $A_\mathrm{C} = 8.66 \pm 0.17$. Because of the uncertainties of the $\log gf$ for these $3s$–$3p$ lines, we give them only weight 1.

Table 1 gives the atomic and solar data and results for the 19 C I lines that we consider to be good indicators of the solar carbon abundance. The mean solar abundance is $A_\mathrm{C} = 8.59 \pm 0.05$, in very good agreement with results derived from the CH vibration-rotation lines. The forbidden line of C I, $2p^2\,^1D_2$–$2p^2\,^1S_0$ at $\lambda 8727.126$ has also been added as a good indicator of the carbon abundance. A new measurement of its equivalent width leads to $W_\lambda = 6.0 \pm 0.8$ mÅ, after correction for a small contribution, 0.15 mÅ, by a Fe I line (Lambert & Ries, 1977). Its transition probability has been recomputed and rediscussed by Nussbaumer & Rusca (1979): $A = 0.529\ \mathrm{s}^{-1}$, i.e. $\log gf = -8.22$, with an accuracy of the order of 5%. With these atomic and solar data, we derive $A_\mathrm{C} = 8.61 \pm 0.06$, in excellent agreement with the results from other carbon abundance indicators.

Table 1. C I lines in the solar spectrum

Transition	$\lambda(\mathring{A})$	$E_{exc}^{low}(eV)$	W_λ(m $\mathring{A}$)	log gf^1	A_C	Weight
$3s-3p$						
$^3P_1^o - ^3D_2$	10753.985	7.49	48.7	- 1.631	8.60	2
$^3P_1^o - ^3S_0$	9603.030	7.48	96.2	- 0.908	8.60	2
$^1P_1^o - ^1S_0$	8335.149	7.68	113.0	- 0.446	8.61	2
$3s-4p$						
$^3P_2^o - ^3D_1$	4775.907	7.49	17.5	- 2.23^2	8.73	1
$^1P_1^o - ^1P_1$	5380.336	7.68	25.0	- 1.74^2	8.63	1
$^1P_1^o - ^1D_2$	5052.167	7.68	40.0	- 1.40^2	8.59	1
$3p-3d$						
$^1P_1 - ^1P_1^o$	10123.871	8.54	109.2	- 0.013	8.66	2
$^3D_1 - ^3F_2^o$	11748.220	8.64	146.0	- 0.403	$(8.40)^4$	1
$^3D_2 - ^3F_2^o$	11777.540	8.64	61.0	- 0.502	$(8.48)^4$	1
$^3D_3 - ^3D_3^o$	11659.68	8.65	111.5	- 0.036	8.58	1
$^3P_1 - ^3P_1^o$	12569.04	8.85	53.7	- 0.573	8.52	1
$^3P_1 - ^3P_0^o$	12562.12	8.85	64.7	- 0.500	8.59	2
$^3P_1 - ^3P_2^o$	12581.59	8.85	59.4	- 0.528	8.55	2
$^3P_0 - ^3P_1^o$	12549.48	8.85	62.5	- 0.534	8.59	3
$^1S_0 - ^1P_1^o$	21023.13	9.17	102.6	- 0.300^3	8.61	2
$3p-4s$						
$^1P_1 - ^1P_1^o$	10541.226	8.54	22.0	- 1.174^3	8.53	1
$^3D_3 - ^3P_2^o$	11895.75	8.65	126.4	0.033	8.61	1
$^3D_2 - ^3P_1^o$	11892.91	8.64	90.5	- 0.234	8.54	2
$^3D_2 - ^3P_2^o$	11848.73	8.64	51.3	- 0.660	8.51	1
$^3D_1 - ^3P_1^o$	11862.99	8.64	49.3	- 0.670	8.49	1
$^3P_2 - ^3P_2^o$	14782.98	8.65	56.0	- 0.578	$(8.21)^4$	1
$^1D_2 - ^1P_1^o$	17448.60	9.00	198.0	0.034	8.63	2

[1] mean of Nussbaumer and Storey (1984) and Luo and Pradhan (1989) for the multiplet values; relative intensities from the intermediate coupling results of Nussbaumer and Storey (see text);

[2] see text for a discussion of the $3s-4p$ transitions;

[3] from Luo and Pradhan (1989; see text);

[4] abundance results disregarded when taking the mean (see text).

Stürenburg & Holweger (1990) very recently investigated the non-LTE effects on the abundances derived from C I and [C I] lines. From their non-LTE abundance corrections, we find $A_C = 8.55 \pm 0.05$, a value that is ten percent lower than our LTE value.

5. Summary and conclusions

This analysis of the vibration-rotation lines of CH in the solar infrared spectrum obtained from space has permitted us to identify a much larger number of lines than ever detected in the laboratory between 3.3 and 4.0 μm. More than 100 of these lines have been used to determine an accurate value of the solar abundance of carbon, $A_C = 8.60 \pm 0.05$.

We also discussed other carbon abundance indicators; the results are summarized below:

CH vibration-rotation (104 lines)	$A_C = 8.60 \pm 0.05$;
C_2 Swan (20 lines)	$A_C = 8.61 \pm 0.03$;
C_2 Phillips (20 lines)	$A_C = 8.58 \pm 0.05$;
CH (A–X) (9 lines)	$A_C = 8.60 \pm 0.04$;
C I (19 lines)	$A_C = 8.59 \pm 0.05$;
[C I] (1 line)	$A_C = 8.61 \pm 0.06$.

The excellent agreement between these different results is encouraging although, as discussed in Sect. 4, some of the solar abundance indicators are more accurate than others. This agreement between various independent determinations results from a careful selection of the lines, an accurate measurements of the equivalent widths and a very careful discussion and selection of the atomic and molecular data to be used.

Our final recommended solar abundance of carbon is $A_C = 8.60 \pm 0.05$. This value is only 0.07 dex smaller than the value recommended by one of us (Lambert 1978). As this abundance is derived from different atomic and molecular species that respond in opposite ways to temperature modifications of the solar model, the recommended solar abundance of carbon should be insensitive to slight temperature changes. Furthermore, the very good agreement between the atomic (C I and [C I]) and molecular (CH vibration-rotation, CH electronic, C_2) results is a further argument in favour of the photospheric model used.

In the course of this study, we also found support in favour of the most recent lifetimes of the upper level of the C_2 Swan band and of the high value, $D_0^0 = 6.21$ eV, of the dissociation energy of C_2 (Sect. 4.2); and in favour of the very recent theoretical transition probability of the C_2 Phillips band, which is about 1.5 times larger than the experimental results (Sect. 4.3). The solar CH $A-X$ lines also show that the theoretical lifetime or f-value for the 1–1 band is to be preferred to the experimental lifetime which is too low because of the influence of predissociation. The C I lines demonstrate once more the need for high precision gf- values in solar spectroscopy.

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