ON THE ABUNDANCE OF CHLORINE IN THE SUN

D. L. LAMBERT
Department of Astronomy, University of Texas at Austin, Austin, Texas, U.S.A.

and

E. A. MALLIA
Department of Astrophysics, University of Oxford, Oxford, England

and

J. BRAULT
Kitt Peak National Observatory*, Tucson, Ariz., U.S.A.

(Received 26 March, 1971)

Abstract. A low-noise photoelectric scan which includes the predicted position of the Cl I transition 4s 4P_{5/2}-4p 4D_{9/2} provides inconclusive evidence for the presence of the line in the solar photospheric spectrum. An upper limit log N(Cl) ≤ 5.5 is derived. It is pointed out that the fundamental vibration rotation band of HCl at 3.3 μ should be detectable in the sunspot spectrum unless log N(Cl) < 4.6. Sunspot spectra may also provide the isotopic abundance ratio N(Cl^{35})/N(Cl^{37}).

A new derivation of the chlorine abundance for the Orion nebula is presented: log N(Cl) ≈ 5.8. It is suggested that a cosmic abundance log N(Cl) = 5.5 to 5.8 be adopted.

1. Introduction

The compilation of a universal or cosmic abundance table for nuclides is greatly dependent on analyses of meteorites. Raw meteoritic abundances for volatile elements, e.g. chlorine, are unsatisfactory and subject to large, uncertain correction factors. Hence, a determination of the solar abundance of chlorine is of interest.

An estimate of the solar abundance of chlorine was presented earlier (Lambert and Mallia, 1968). A tentative identification of the strongest line in the 4s–4p transition array at λ_{lab}=8375.943 Å led to the abundance log N(Cl) = 5.65 on the standard scale log N(H)=12.00. New photoelectric scans are discussed in this paper. Alternative possibilities of defining the solar chlorine abundance are also outlined.

2. Observations

The earlier series of observations of λ8375 were obtained with the Oxford spectrometer (Blackwell et al., 1967). Conditions were far from optimum owing to severe blending of λ8375 with atmospheric water vapor lines. In addition, an objection may be raised concerning the use of a photomultiplier with a tri-alkali cathode. This cathode has a very low sensitivity at 8375 Å relative to shorter wavelengths. Hence,

* Operated by the Association of Universities for Research in Astronomy Inc., under contract with the National Science Foundation.

Copyright © 1971 by D. Reidel Publishing Company, Dordrecht-Holland

© Kluwer Academic Publishers • Provided by the NASA Astrophysics Data System
it is possible that a small light leak from other orders of the grating may have provided a spurious weak absorption line.

New photoelectric scans have been made with the Oxford installation on the Gornergrat in the Swiss Alps; this spectrometer is described by Blackwell et al. (1969). The detector was a RCA 7102 tube with a Si cathode, which was cooled by dry ice. The sensitivity of the cathode has a maximum near 9000 Å. Contamination from the next higher order is excluded as there are no lines deeper than 1% at or near the position corresponding to 8375.9 Å. The fact that the rotational shift of the 'Cl I' line is the same as that of neighbouring Fraunhofer lines argues against contamination from higher orders; lines from lower orders in positions corresponding to 8375.9 Å are all produced by telluric H₂O lines which would not show any rotational wavelength shift. Finally it may be pointed out that the fact that the central intensities of 8375.9 Å from the Oxford and Gornergrat scans agree closely (though the Oxford monochromator has much the larger dispersion) indicates that contamination in the former was not substantial. Photoelectric scans have also been obtained with the Kitt Peak double-pass spectrometer.

In January 1970, the region 8370–8380 Å was scanned at the Gornergrat on a cold

![Diagram](image)

**Fig. 1.** The photospheric spectrum near 8375 Å. The spectrum has been corrected for instrumental broadening.
Fig. 2. The photospheric spectrum near 8375.9 Å shown on an expanded scale. The dotted and dashed profiles correspond to a plausible resolution of the Fraunhofer line 8375.903 Å into two components; the broad dashed profile centered on 8375.943 is the possible Cl I contribution.

dry day with spectrometer slit widths corresponding to \( \lambda/\Delta \lambda = 2.05 \times 10^5 \). Water vapor lines are considerably reduced in strength. A portion of the scan is shown in Figure 1. This scan was obtained with the entrance slit set at the center of the disk. Two other scans were obtained in July, 1970, under moderately dry conditions with the entrance slit set at the center of the disk and at the limb (\( \cos \theta = 0.22 \)). In the available Kitt Peak spectra, the water vapor line intensities are slightly greater than in the July scans.

3. Discussion

The scans, which are illustrated in Figures 1 and 2 provide important new information. A weak Fraunhofer line is observed at \( \lambda = 8375.903 \pm 0.010 \) mÅ; this wavelength is derived from the January 1970 scan by interpolating between the measurements given by Moore et al. (1966). The central depth of the line is \( r_0 = 1.1 \pm 0.2\% \) and the total half width is \( \Delta \lambda_{1/2} = 105 \pm 10 \) mÅ. The line is asymmetrical; the red wing is the stronger. The July 1970 pair of scans at the center and limb of the disk provide additional measurements but, owing to the greater intensity of the water vapor lines, the wavelength measurements of solar lines would be less accurate. In the limb scan, the weak line is symmetrical and there is no significant change in equivalent width. The limb scans confirm that this weak line is solar in origin; the wavelength displacements of the line and neighbouring identified Fraunhofer lines due to solar rotation are identical.

A control pair of scans were obtained of Si I lines \( \lambda \lambda 8670.2, 8671.3 \) and 8680.4 at the
center and limb of the disk. The profiles of S1 lines and possible ClI identifications should have similar total half-widths and center-limb variations because the atomic weights of S and Cl differ by less than four atomic mass units and the excitation potentials are similar (7.97 eV for S1 and 8.9 eV for ClI). The measured half-width for S1 lines at the center of the disk is $\Delta \lambda_{1/2} = 165 \pm 10$ mÅ. The S1 lines weaken drastically towards the limb; $W_{\lambda} (\cos \theta = 0.22) / W_{\lambda} (\cos \theta = 1.0) \approx 0.4$ in reasonable accord with a model atmosphere prediction.

The new scans of $\lambda 8375$ and the control S1 lines provide the following evidence which does not support the identification of the weak Fraunhofer line $\lambda = 8375.903$ with the ClI transition:

1. The observed total half-width is considerably smaller than the predicted half-width for the ClI line as obtained from the S1 lines: $\Delta \lambda_{1/2} = 105 \pm 10$ is observed but $\Delta \lambda_{1/2} = 165 \pm 10$ mÅ is the predicted width.

2. The center-limb variation of $\lambda 8375.903$ is not that expected of a high-excitation line. In this respect it may be pointed out that the ClI line should show a greater weakening to the limb than the S1 lines. Its excitation potential is nearly 1 eV higher.

3. The wavelength measurement from the best scan is $40 \pm 10$ mÅ to the blue of the predicted ClI wavelength. The ClI transition has a predicted wavelength $\lambda_{\text{air}} = 8375.943 \pm 0.003$ Å according to levels determined by Radziemski and Kaufman (1969). The expectation that $\lambda_{\odot} = \lambda_{\text{air}}$ for the ClI line was discussed earlier (Lambert and Mallia, 1968).

The evidence appears decisive; the line with $\lambda = 8375.903$ is not attributable to the ClI transition, although it is possible that ClI provides the observed asymmetry of this unidentified line. A profile analysis indicates that a line at the predicted wavelength and with the predicted halfwidth ($\Delta \lambda_{1/2} = 165$ mÅ) may be inserted to obtain $r_0 = 0.3\%$ and $W_{\lambda} = 0.5$ mÅ (see Figure 2). It may be predicted that this composite profile should lose its asymmetry at the limb which is in accord with the observations. Since the asymmetry is slight, the result is conservatively presented as an upper limit:

$$W_{\lambda} \leq 0.5 \text{ mÅ} \quad \text{for} \quad \lambda 8375 \quad \text{of} \quad \text{ClI}.$$ 

4. The Cl Abundance

Absolute transition probabilities for members of the 4s–4p transition array of ClI were recently measured using a gas driven shock tube (Bengtson et al., 1971). The line $\lambda 8375$ was self-absorbed and no acceptable measurement of the transition probability was obtained. Bengtson (1970) suggested that this omission be remedied by normalizing intermediate coupling calculations to the experimental results for other lines in the array. This procedure yields $\log gf = +0.25 \pm 0.11$ for $\lambda 8375$. The uncertainty of $\pm 30\%$ is the quoted experimental uncertainty. The intermediate coupling calculations by Cowan (private communication to Bengtson et al., 1971) give $\log gf = +0.53$. The coulomb approximation radial integral with LS-coupling line strengths corre-
spond to \( \log gf = +0.44 \) (Lambert and Mallia, 1968). The value \( \log gf = +0.25 \) is adopted.

The model atmosphere presented by Gingerich (1969, 1970) as an improvement on the Bilderberg Conference Atmosphere (Gingerich and de Jager, 1968) is employed in a line profile calculation which assumes that the line is formed by pure absorption. The upper limit for the Cl abundance is \( \log N(\text{Cl}) \leq 5.5 \) for \( W_\lambda \leq 0.5 \) mÅ. If either of the theoretical calculations of the oscillator strength are preferred, a lower abundance limit is obtained. The results are not affected by the recent revision of the Fe abundance which enters into the calculation of the gas and electron pressure.

5. Future Prospects

The present failure to provide a positive identification of the Cl\( ^1 \) transition is attributable to the accidental blending with the unidentified line at \( \lambda 8375.903 \) Å. The capability of existing spectrometers would permit detection of weaker but unblended lines. Six lines have predicted intensities within a factor of three of the present upper limit for \( \lambda 8375 \). On inspection of the standard atlas for the solar near-infrared spectrum (Delbouille and Roland, 1963), two are quite obviously severely blended, and four lines are located in regions worthy of closer examination. The strongest line at \( \lambda_{\text{lab}} = 9121.146 \) Å was searched for on Kitt Peak and Gornergrat scans. It is positioned within a complex of water vapor and CN lines with a disappointing upper limit for \( W_\lambda \) of about 1 mÅ for the chlorine component. Of the three remaining candidates (\( \lambda \lambda 8585.97, 9288.856, \) and 8948.063 Å), \( \lambda 8948 \) appears to be the best choice but, with a predicted intensity \( W_\lambda \approx 0.1 \) mÅ, the probability of a positive identification is slight.

Hall and Noyes (1969) reported the identification of the fundamental vibration-rotation band of HF in sunspot spectra at 2.3 \( \mu \). This report prompted calculations of the expected intensity of the HCl fundamental and first overtone bands at 3.3 and 1.7 \( \mu \) respectively.

Recent laboratory measurements of the line strengths are given by Toth et al. (1970), who also provide references to earlier experimental work. The dissociation energy of HCl is known: \( D_0 = 4.431 \) eV (Gaydon, 1968). The selected sunspot model is defined by the reciprocal temperature distribution

\[
\theta_u(\tau_0) = \theta_{ph}(\tau_0) + 0.4
\]

where \( u \) and \( ph \) denote the sunspot umbra and photosphere respectively. This model is not definitive but the predicted infrared continuum intensities are in good accord with the observations of a large sunspot tabulated by Hall and Noyes. Furthermore, the predicted HF fundamental equivalent widths are within a few per cent of the observed values for a large sunspot; this calculation uses the experimental line strengths referenced by Hall and Noyes and their derived abundance of fluorine.

The equivalent widths in both bands attain a maximum value at about \( J = 9 \) in the
The predicted equivalent widths \( W_\lambda \) and central line depths \( r_0 \) for \( R(9) \) of \( \text{H}^{35}\text{Cl} \) are

<table>
<thead>
<tr>
<th>Band</th>
<th>( \lambda ) (microns)</th>
<th>( \cos \theta )</th>
<th>( W_\lambda ) (mÅ)</th>
<th>( r_0 ) (per cent)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1–0</td>
<td>3.267</td>
<td>1.0</td>
<td>12</td>
<td>23</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.7</td>
<td>14</td>
<td>27</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.5</td>
<td>17</td>
<td>33</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.3</td>
<td>22</td>
<td>43</td>
</tr>
<tr>
<td>2–0</td>
<td>1.721</td>
<td>0.7</td>
<td>0.2</td>
<td>1.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2.7</td>
<td>3.3</td>
<td>4.3</td>
</tr>
</tbody>
</table>

The calculations assume a total abundance \( \log N(\text{Cl}) = 5.5 \) and the terrestrial isotopic abundance ratio \( N(35\text{Cl})/N(37\text{Cl}) = 3.05 \).

The results strongly suggest that the fundamental band of HCl should be located when the mapping of the sunspot spectrum is extended to the 3 to 4 micron atmospheric window; several lines, including \( R(9) \), will be too heavily blended with telluric absorption lines. The isotopic abundance ratio may also be obtainable: \( W_\lambda (\text{H}^{37}\text{Cl}) = W_\lambda (\text{H}^{35}\text{Cl})/3.05 \). Absence of \( \text{H}^{35}\text{Cl} \) lines, say \( r_0 < 0.5 \) per cent, corresponds to the abundance limit \( \log N(\text{Cl}) \leq 4.6 \) for a spot observed near the limb. It may also be possible to detect the weaker but more favorably places \( 2–0 \) lines; the above calculations are dependent on the model and the recent spot model by Stellmacher and Wiehr (1970) results in larger equivalent widths, e.g. \( W_\lambda \approx 2 \) mÅ is predicted for \( 2–0 \) \( R(9) \). Accurate wavelengths for the \( 1–0 \) and \( 2–0 \) bands are obtainable from Rank et al. (1965).

Higher overtone bands are located in the near infrared and are accessible to observation; for example, the \( 4–0 \) band is near 9000 Å but, unfortunately, the predicted intensity of the strongest line is \( W_\lambda \ll 0.1 \) mÅ for \( \log N(\text{Cl}) = 5.5 \).* No HCl vibration rotation bands should be detectable in the photospheric spectrum; \( W_\lambda < 0.05 \) mÅ is predicted for the fundamental. The electronic transitions of HCl are in the ultraviolet \( (\lambda < 3000 \) Å) and they will be obliterated by overlying Fraunhofer lines.

The chlorine resonance lines should be searched for in the emission line spectrum of the chromosphere and corona. With the rule of thumb that the intensities of the resonance lines of two ions are approximately proportional to the relative abundances, the failure to identify chlorine lines on presently available spectrograms and scans is not unexpected.

The cataloguing of the forbidden line spectrum of the corona remains incomplete. Jefferies (1969) noted that no observed lines occurred near the predicted wavelengths for forbidden lines of chlorine. On the assumption that the line intensity ratio for \([\text{Ar}xix]/[\text{Cl}xiii] \) and \([\text{A} x]/[\text{Cl} ix] \) must approximate the abundance ratio \( N(A)/N(\text{Cl}) \), the failure to locate the chlorine lines is consistent with the present estimate of the abundance: \( \log N(\text{Cl}) \leq 5.5 \).

* The intensity ratios of overtones and fundamental are very similar for HF and HCl (Cashion, 1963). The reported identification of the \( 4–0 \) HF band (Wöhl, 1970) cannot be given great weight because the predicted intensity for these lines is \( W_\lambda \ll 0.1 \) mÅ.
6. Chlorine Abundances in B Stars and Gaseous Nebulae

The chlorine abundance in the B star $\gamma$ Pegasi was derived by Aller and Jugaku (1959), and a revised value is quoted by Aller (1961): $\log N(\text{Cl}) = 6.25$. A reinvestigation is desirable to study the possibility of an over abundance of chlorine with respect to the Sun.

Forbidden lines of chlorine have been identified in the emission line spectrum of the Orion nebula; recent quantitative measurements of [Cl III] were reported by Aller and Walker (1970) and the [Cl IV] nebular line was identified by Andrillat and Houziaux (1969). A simple abundance analysis is presented.

The distribution of ions within the nebula is determined by the supply of ionizing photons, which is effectively controlled by the helium ionization edge $\text{He}^+ \rightarrow \text{He}$. Inside the $\text{He}^+$ zone, species with ionization potentials between 24.6 and 54.4 eV will be found. Thus chlorine abundance may be derived from the following approximate relations

$$\frac{N(\text{Cl})}{N(S)} \approx \frac{N(\text{Cl}^{2+})}{N(S^{2+})} \quad \text{and} \quad \frac{N(\text{Cl})}{N(O)} \approx \frac{N(\text{Cl}^{2+})}{N(O^{2+})}$$

and the sulphur and oxygen abundances determined by Peimbert and Costero (1969). The sulphur and oxygen ratios possibly provide upper and lower limits respectively. The line intensities corrected for interstellar reddening were taken from Peimbert and Costero (1969) and Aller and Walker (1970). The ionic densities are obtained from the relations provided by Aller and Czyzak (1968) and Aller and Walker (1970). The results are

$$\log N(\text{Cl}) \approx 5.8 \text{ from [Cl III]/[S III] ratios},$$

$$\approx 5.9 \text{ from [Cl III]/[O III] ratio.}$$

The result $\log N(\text{Cl}) = 5.8$ is adopted. This is not significantly greater than the present upper limit for the solar abundance.

Of especial interest are the abundance analyses for planetary nebulae; Aller and Czyzak (1968) quote $\log N(\text{Cl}) = 6.9$. This is markedly greater than the Orion value and the solar upper limit. A real abundance difference may be indicated because identical collision cross-sections were used in the Orion and planetary nebulae analyses.

7. The Cosmic Abundance of Chlorine

A cosmic abundance of $\log N(\text{Cl}) = 5.5$ to 5.8 is suggested. This is to be preferred to the value in the recent compilation (Cameron, 1968) which was weighted in favor of the meteorite results: $\log N(\text{Cl}) = 4.84$ when the scale is normalized to the solar silicon abundance (Lambert and Warner, 1968).

Acknowledgements

The Gornergrat Observatory forms part of the Hochalpine Forschungsstation Jung-
fraujoch. Operation of the Oxford spectrometer is financed by a grant from the Science Research Council. We wish to thank Professor D. E. Blackwell for an invitation to D. L. Lambert to observe at the Gornergrat Observatory, and Dr A. D. Petford for design of the cooled photomultiplier assembly.

References

Gingerich, O.: 1970, private communication.