THE ABUNDANCE OF IRON IN THE SOLAR CORONA

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Summary

A comparison of the observed intensities of lines within Fe X, XI, XIV and XV multiplets, in the far ultra-violet solar spectrum, enables the population of the excited level of the ground term \( N_u \) to be found, relative to that of the ground level \( N_g \). This factor \( N_u/N_g \) is needed in the determination of the abundance from the equivalent widths of forbidden emission lines in the near-visible spectrum. Hence, it has been possible to calculate the abundance of iron in the solar corona. The value obtained is \( \log N(Fe)/N(H) = -4.30 \). This is in accordance with other coronal estimates, but is an order of magnitude greater than the value from photospheric determinations. The values of \( N_u/N_g \) have also been used in combination with theoretical excitation cross-sections, to calculate the electron density, \( N_e \).

1. Introduction. The apparent difference between the abundance of iron in the solar photosphere and corona has been a problem for many years. Values of the iron abundance in the photosphere have been derived by Goldberg, Kopp & Dupree (1), Aller, O’Mara & Little (2), Warner (3), and Letfus (4) and earlier authors. Pottasch (5, 6), Woolley & Allen (7), and Shklovskii (8) have derived values of the abundance in the corona using the forbidden lines in the visible region of the spectrum. Pottasch (9) has also derived a value from an analysis of the far ultra-violet permitted lines. Table I gives the abundances found by the above authors.

<table>
<thead>
<tr>
<th></th>
<th>Photosphere</th>
<th>Corona</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( \log N(Fe) )</td>
<td>( \log N(Fe) )</td>
</tr>
<tr>
<td>Goldberg et al.</td>
<td>6.64</td>
<td>Pottasch (from permitted lines) 7.60</td>
</tr>
<tr>
<td>Aller et al.</td>
<td>6.59</td>
<td>Pottasch (from forbidden lines) 7.84</td>
</tr>
<tr>
<td>Warner</td>
<td>6.81</td>
<td>Pottasch (from forbidden lines) 7.87</td>
</tr>
<tr>
<td>Letfus</td>
<td>6.76</td>
<td>Woolley &amp; Allen (from forbidden lines) 7.8</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Shklovskii (from forbidden lines) 8</td>
</tr>
</tbody>
</table>

In the present paper the approach is the same as that of Pottasch (5, 6) and earlier authors, in that the equivalent widths of the forbidden emission lines are used to determine \( N_u/N_e \), where \( N_u \) is the population of the excited level of the ground term, and \( N_e \) is the electron density. However, it is shown that the permitted lines in the far ultra-violet part of the spectrum may be used to determine the population ratio \( N_u/N_g \), where \( N_g \) is the ground level population. Only relative excitation cross-sections and relative line intensities are needed.
to find the ratio \( N_u/N_g \). The abundance can then be derived from the values of \( N_g/N_e \) in either of two ways. The ratio \( N_u/N_g \) has been calculated by other authors using the theoretical cross-sections and an assumed value of the electron density \( N_e \). Therefore, as \( N_u/N_g \) has been found by a different method, the electron density, \( N_e \), can be calculated.

2. The forbidden lines

(a) The determination of \( N_u/N_e \). The intensity of a forbidden line of a coronal ion is measured as the equivalent width in terms of the background continuous emission due to electron scattering. For optically thin conditions, as in the solar corona, the emission at any point, per cm\(^3\) in all directions, in a forbidden line is given by

\[
A_u N_u h\nu
\]

where \( N_u \) is the number density of the upper level, and \( A_u \) is the transition probability for emission.

The continuous emission, in all directions, due to electron scattering is given by

\[
4\pi \sigma D(r) F(\lambda) N_e
\]

where the dilution factor is \( D(r) = \frac{1}{2} [1 - (1 - r^2)^{1/2}] \), and \( r \) is the radial distance from the centre of the Sun measured in solar radii; \( \sigma = 6.65 \times 10^{-25} \text{ cm}^2 \) is the cross-section for electron scattering and \( F(\lambda) \) is the mean solar emission (erg/cm\(^2\)/sterad/\(\AA\)) as tabulated by Allen (10).

The equivalent width, \( W(r) \), at radial distance \( r \), is given by

\[
W(r) = \frac{N_u}{N_e} (r) \frac{A_u h\nu}{4\pi} \frac{1}{D(r) F(\lambda) \sigma}
\]  

There are two minor corrections which should be made to the value of \( N_u/N_e \) as calculated from the observed equivalent width, according to van de Hulst (11).

(i) at heights between 5000 km and 70000 km about 91% of the continuous emission is formed by electron scattering. The observed equivalent widths have therefore been increased by 9%.

(ii) The equivalent width, \( W(r) \), refers to the emission per cm\(^3\) at radial distance \( r \), but the observed equivalent width, \( W(\rho) \), refers to the emission per cm\(^3\) at projected radial distance \( \rho \), after integration along the line of sight. \( W(\rho) \) will be smaller than \( W(r) \) at \( \rho = r \), as \( W \) generally decreases with increasing \( r \), and the relation between the two values is given by

\[
W(\rho) \approx W(r) \left[ \frac{H_{\text{line}}}{H_{\text{continuum}}} \right]^{1/2}
\]

where \( H \) is the scale height. The values of the scale heights used will be discussed in the following section.

(b) Observational data. The observational data for the forbidden lines have been chosen bearing in mind that they should refer to the same region of the solar atmosphere as that in which the permitted lines are found. The observed intensities of the permitted lines in the far ultra-violet part of the spectrum include emission integrated over the disk and along the line of sight. If the transition region, from the chromosphere to the corona, is below a height of 4000 km above
the photosphere, then the permitted lines will be formed at heights at about 5,000 km and above. The data of Athay & Roberts \((12)\) for the forbidden lines include emission from heights of about 3,000 km and above, and are therefore suitable to use in a comparison with the permitted lines. The observations of Athay & Roberts were made at the eclipse on 1952 February 25, and include values of the equivalent widths of lines of Fe X, \(\lambda 6374\), Fe XI, \(\lambda 7892\) and Fe XIV, \(\lambda 5303\) in quiet and active regions. The Fe XV, \(\lambda 7060\), line was observed only in the active regions, and its intensity is given relative to the Fe XIV line in the same region. The spectroheliograms of Purcell, Garrett & Tousey \((13)\) in the far ultra-violet show the Fe XV permitted line at \(\lambda 284\) to be confined mainly to plage regions. This is support for the assumption that the observations of the ultra-violet and visible lines refer to the same region of the solar atmosphere. The values of \(W\) listed in Table II refer to mean conditions of activity for Fe X and XI, to greater than average activity for Fe XIV, and to an active region for Fe XV.

The scale heights of the lines and the continuous emission are also needed. Athay & Roberts give the scale height of the Fe XI, \(\lambda 7892\), line as 20,000 km. It will be assumed that the scale height of the Fe X line is the same as that of Fe XI. From Petri's \((14)\) observations, the scale height of the Fe XIV line, for heights above 17,000 km is about 30,000 km. This value will also be used for the Fe XV line. The scale height of the continuous emission at the 1952 eclipse was about 70,000 km according to the observations of Athay et al. \((15)\). It is assumed that the same value of the scale height of the continuous emission can be used with Petri’s observations.

Table II gives the spectroscopic data for the forbidden lines, the values of the equivalent widths, and the calculated values of \(N_u/N_e\) including the corrections discussed in section 2 \((a)\).

Table II

<table>
<thead>
<tr>
<th>Ion</th>
<th>Transition</th>
<th>Wavelength ((\AA))</th>
<th>Transition probability ((s^{-1}))</th>
<th>(W(\rho)) ((\AA))</th>
<th>(N_u/N_e) ((10^{-7}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fe X</td>
<td>(3,^2P_3/2 \rightarrow 3,^2S_1/2)</td>
<td>6374</td>
<td>69</td>
<td>2.7</td>
<td>2.63</td>
</tr>
<tr>
<td>Fe XI</td>
<td>(3,^2P_3/2 \rightarrow 3,^2S_1/2)</td>
<td>7892</td>
<td>44</td>
<td>5.9</td>
<td>7.23</td>
</tr>
<tr>
<td>Fe XIV</td>
<td>(3,^2P_3/2 \rightarrow 3,^2S_1/2)</td>
<td>5303</td>
<td>60</td>
<td>10</td>
<td>8.8</td>
</tr>
<tr>
<td>Fe XV</td>
<td>(3,^2P_3/2 \rightarrow 3,^2S_1/2)</td>
<td>7060</td>
<td>38</td>
<td>1.0</td>
<td>1.24</td>
</tr>
</tbody>
</table>

3. The permitted lines

\((a)\) The required coefficients. The collisional excitation rate is given by Van Regemorter \((16)\) as

\[
C_{ij} = 1.7 \times 10^{-8} N_e T_e^{-1/2} W_{ij}^{-1} f_{ij} \times 10^{-5} 40 W_{ij}/T_e P \left( W_{ij}/kT_e \right) \text{s}^{-1}
\]

where \(W_{ij}\) is the excitation energy in electron volts, \(f_{ij}\) is the oscillator strength, and \(P\) is an integral of the gaunt factor, given by Van Regemorter as a function of \(W_{ij}/kT_e\). A more recent expression by Burgess \((17)\) increases the rates by about a factor of 1.5.
The ionization ratio \( N(X^{+m+1})/N(X^{+m}) \) has been calculated for each ion using the following ionization rate coefficient and recombination coefficient. The ionization rate coefficient is that given by Burgess & Seaton (18),

\[
q(X^{+m}) = 2 \cdot 10^{-8} T_e^{1/2} \sum_i \xi_m(n, l) I_m^{-2}(n, l) \cdot 10^{-5040f_m(n, l)/T_e} \text{ cm}^3 \text{ s}^{-1}
\]

where \( n \) is the principle quantum number of the outer electrons of \( X^{+m} \); \( \xi_m(n, l) \) is the number of electrons with quantum numbers \( n, l \); \( I_m(n, l) \) is the corresponding ionization potential in electron volts. The radiative recombination rate coefficient, also from Burgess & Seaton, is

\[
\alpha(X^{+m}) = 1.3 \times 10^{-9} (m + 1)^2 I_m^{1/2} \text{ cm}^3 \text{ s}^{-1}
\]

and for di-electronic recombination the general formula of Burgess (19) has been used,

\[
\alpha(d-e) = 3.3 \times 10^{-10} f_i T_e^{-5/2} (z + 1)^2 e_{ij}^{1/2} A(x) B(z) e^{-E/kT}
\]

where

\[
e_{ij} = \frac{1}{n_i^2} - \frac{1}{n_j^2},
\]

\( n_i, n_j \) are the effective principle quantum numbers of the states \( i, j \), and \( z \) is the charge on the recombining ion.

\[
x = (z + 1) e_{ij}, \quad \frac{E}{kT} = (z + 1)^2 e_{ij} \cdot 1.58 \times 10^6 T_e^{-1} a^{-1}
\]

\[
a \simeq 1 + 0.015 \cdot z^3(z + 1)^{-2}
\]

for \( E/kT \leq 5 \cdot 10^{-7} \), and \( x > 0.05 \).

\( A(x) \) and \( B(z) \) are tabulated by Burgess. The sum is over all bound states of the recombining ion.

From \( \frac{N(X^{+m+1})}{N(X^{+m})} \), the ratio \( \frac{N(X^{+m})}{N(E)} \) can be found, where \( N(E) \) is the number density of the element concerned.

The maximum emission in a given line occurs when the function

\[
g(T) = T_e^{-1/2} 10^{-5040W/T_e} \frac{N(X^{+m})}{N(E)}
\]

has its maximum value, (Pottasch 20). Because this function falls steeply away from its maximum value, it can be assumed that 70% of the observed line intensity is formed in the region where \( T_e = T_{\text{max}} \), the temperature at \( g(T)_{\text{max}} \).

In the cases to be considered, the relative collisional excitation rate coefficients for lines within a given multiplet, depend only on the relative \( f \)-values of the upward transitions, as the difference in the term \( W^{-1.10^{-5040W/T_e}} \) in equation (2), for lines within a multiplet, may be neglected. From a given excited level, electrons will return to the levels of the ground term in proportion.
to the emission oscillator strengths. Thus in the following calculations in which the intensity of two lines within a given multiplet is compared, only the relative values of the oscillator strengths need be known.

(b) Identifications, intensities and $f$-values for permitted transitions in Fe X to Fe XV. The lines from transitions of the type $3s^23p^2 - 3s^23p^13d$ in Fe X, XI and XIV are amongst those classified by Gabriel, Fawcett & Jordan (21, 22). The above authors (21), pointed out that in the laboratory sources used for the work on classifications, the electron density is high enough for the levels of the ground term to be populated statistically. But that in the solar corona, where the electron density is much smaller, lines terminating on an excited level of the ground term are weaker relative to lines terminating on the ground level. This accounts for the fact that in the solar spectrum the relative intensities of lines in the $3p^2P - 3d^2D$ multiplet in Fe XIV are not as expected from Garstang’s $f$-values. The relative intensities of the lines from Zeta agree with those expected using Garstang’s $f$-values. The Fe XV wavelengths are from the work of Edlen. The lines from the $3s^23p^2P - 3s3p^2P$ multiplet in Fe XIV were identified with solar lines by the present author using Garstang’s (23) predicted wavelength. The same lines have been suggested independently by several writers.

The solar line intensities are from Hinteregger (24), Hall et al. (25), (26), found from photo-electric observations made during rocket flights in 1963 May, 1964 March and 1961 August respectively.

The $f$-values for Fe XIV have been calculated by Garstang (23), and those for Fe XV by Froese (27). For other ions the relative $f$-values in LS-coupling have been found using the tables of relative line strengths given by Allen (10). The relative intensities of the lines of Fe X, XI and XIV observed in the laboratory sources used for the work on classifications, are in general accordance with those expected in LS-coupling.

The identifications, intensities and $f$-values relevant to the following calculations are given in Table III.

(c) The calculations of $N_u/N_g$. Consider an ion with at least two levels in the ground term:

Let $N_g$ be the number density of the ground level; let $N_u$ be the number density of an excited level of the ground term; let $N_i$ and $N_j$ be the number densities of two levels of an excited term.

In coronal conditions, the important processes contributing to the formation of permitted lines between two terms are:

(i) Collisional excitation by electrons from the ground level, $g$, followed by a radiative transition.

(ii) Collisional excitation from the excited level, $u$, followed by a radiative transition.

According to Seaton (28), excitation by proton impact is important only for populating the excited levels of the ground term. Recombination followed by cascade can be shown to be negligible.

If two lines within a multiplet are observed, one of which may be excited from the two levels of the ground terms $u$ and $g$, and the other from only one level of the ground term, then the population of the excited level of the ground term can be determined. For example, consider the $3s^23p^2P^0 - 3s^23d^2D$ multiplet in Fe XIV, as shown in Fig. 1.
## Table III

The permitted XUV lines

<table>
<thead>
<tr>
<th>Ion</th>
<th>Transition</th>
<th>( J_{lower} )</th>
<th>( J_{upper} )</th>
<th>( \lambda ) (Å)</th>
<th>( f_{l-u} )</th>
<th>( f_{e-u} )</th>
<th>Intensity, ( E ) (erg/cm²/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fe X</td>
<td>( 3p^6-3p^4d ) ( ^3P^0-^3D )</td>
<td>3/2</td>
<td>5/2</td>
<td>174.5</td>
<td>0.90</td>
<td>0.60</td>
<td>1961</td>
</tr>
<tr>
<td></td>
<td>1/2</td>
<td>3/2</td>
<td>175.3</td>
<td>1.00</td>
<td>0.50</td>
<td>0.0102</td>
<td>0.0051</td>
</tr>
<tr>
<td></td>
<td>3/2</td>
<td>3/2</td>
<td>170.6</td>
<td>0.10</td>
<td>0.10</td>
<td>0.090</td>
<td>0.048</td>
</tr>
<tr>
<td>Fe XI</td>
<td>( 3p^6-3p^3d ) ( ^3P-^3D^0 )</td>
<td>2</td>
<td>3</td>
<td>180.4</td>
<td>0.84</td>
<td>0.60</td>
<td>0.0160</td>
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<td></td>
<td>1</td>
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<td>182.2</td>
<td>0.75</td>
<td>0.45</td>
<td>0.0047</td>
<td>0.0024</td>
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<td></td>
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<td>2</td>
<td>178.0</td>
<td>0.15</td>
<td>0.15</td>
<td>0.0051</td>
<td>0.0024</td>
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<td></td>
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<td>1</td>
<td>180.6</td>
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<td>0.25</td>
<td>0.0051</td>
<td>0.0024</td>
</tr>
<tr>
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<td>176.5</td>
<td>0.01</td>
<td>0.02</td>
<td>0.0051</td>
<td>0.0024</td>
</tr>
<tr>
<td>Fe XIV</td>
<td>( 3p-3d ) ( ^2P^0-^2D )</td>
<td>3/2</td>
<td>5/2</td>
<td>219.1</td>
<td>0.50</td>
<td>0.33</td>
<td>0.0015</td>
</tr>
<tr>
<td></td>
<td>1/2</td>
<td>3/2</td>
<td>211.3</td>
<td>0.55</td>
<td>0.27</td>
<td>0.0031</td>
<td>0.0024</td>
</tr>
<tr>
<td></td>
<td>3/2</td>
<td>3/2</td>
<td>220.1</td>
<td>0.072</td>
<td>0.072</td>
<td>0.0031</td>
<td>0.0024</td>
</tr>
<tr>
<td>Fe XV</td>
<td>( 3s^2-3p^3 ) ( ^1S-^1P^0 )</td>
<td>0</td>
<td>1</td>
<td>284.2</td>
<td>0.81</td>
<td>0.27</td>
<td>0.0043</td>
</tr>
<tr>
<td></td>
<td>( 3p^6-3p^3d ) ( ^3P^0-^3D )</td>
<td>2</td>
<td>3</td>
<td>231.9</td>
<td>0.24</td>
<td>0.17</td>
<td>0.0043</td>
</tr>
<tr>
<td></td>
<td>( 3s^2-3p^3 ) ( ^1S-^3P^0 )</td>
<td>0</td>
<td>1</td>
<td>414</td>
<td>0.18</td>
<td>0.06</td>
<td>0.0043</td>
</tr>
</tbody>
</table>
(i) The line $^2P_0^3/2 \rightarrow ^2D_5/2$ may be formed only by collisional excitations from $^2P_0^3/2$, followed by transitions back to the same level. This may be expressed as

$$\text{number of photons } \Phi_{^2P_0^3/2} \propto N_u N_e^3/2 \times ^2P_0^3/2 \times ^2D_5/2 \times (5).$$

The line $^2P_1/2 \rightarrow ^2D_3/2$ may be formed by collisional excitations from the ground level and the excited level, followed by transitions to $^2P_0^1/2$. Then

$$\Phi_{^2P_1/2} \propto N_e \left[ \frac{f_{^2P_0^1/2}}{f_{^2P_0^3/2} + f_{^2P_0^1/2}} \right] . \left[ N_u f_{^2P_0^3/2} + N_u f_{^2P_0^1/2} \right]. \quad (6)$$

Similarly

$$\Phi_{^2P_3/2} \propto N_e \left[ \frac{f_{^2P_0^3/2}}{f_{^2P_0^3/2} + f_{^2P_0^1/2}} \right] . \left[ N_u f_{^2P_0^3/2} + N_u f_{^2P_0^1/2} \right]. \quad (7)$$

Assuming that $\Phi_{^2P_0^3/2} / \Phi_{^2P_0^1/2} = E_{^2P_0^3/2} / E_{^2P_0^1/2}$, where $E$ is the observed intensity, and substituting numerical values from Table III, we find from (5) and (6) that $N(^2P_3/2)/N_g = 0.17$ and from (5) and (7), $N(^2P_3/2)/N_g = 0.12$.

(ii) Fe XIV $3s^23p^2^2P_0^0 \rightarrow 3s^23d^2^2D$. The method can be applied to multiplets for which $\Delta L = 0$, but in this case it will not give an accurate result because it involves the subtraction of two terms of similar size. However, using the value of $N_u/N_g$ calculated in section 1, and the relative oscillator strengths, the values of $\Phi(^2P_0^0^1/2 \rightarrow ^2P_3/2) / \Phi(^2P_0^0^3/2 \rightarrow ^2P_1/2)$ and $\Phi(^2P_0^0^1/2 \rightarrow ^2P_3/2) / \Phi(^2P_0^0^3/2 \rightarrow ^2P_1/2)$ may be calculated. The line $^2P_0^0^1/2 \rightarrow ^2P_3/2$, at 270.5 Å is unblended, and its intensity can be used with the above relative values, to predict the intensity of the lines $^2P_0^1/2 \rightarrow ^2P_3/2$ and $^2P_0^3/2 \rightarrow ^2P_1/2$ at 251.9 Å and 257.4 Å respectively. It is found that only 1/4 of the observed line at 251.9 Å and 1/7 of the observed line at 257.4 Å should be due to Fe XIV. The other components of these lines are Fe XIII $3s^23p^2^3P_2 \rightarrow 3s^23d^2^3S_1$ at 251.8 Å and possibly Fe XVI $3p^2^2P_0^0^1/2 \rightarrow 3d^2^2D_3/2$ at 251.1 Å; Si X $2s^22p^3^3P_0^1/2 \rightarrow 2s^22p^3^3P_1/2$ at 256.6 Å and SX $2s^22p^3^4S_0^0 \rightarrow 2s^22p^3^4P_1/2$ at 257.1 Å, and Fe XIII $3s^23p^2^2P_2 \rightarrow 3s^23p^2^2S_1$ at 257.8 Å.

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The same approach may be used to show that the line at 289·4 Å has eight times the intensity expected from Fe XIV $3s^23p^23P^0_{2s/2} - 3s3p^23S_{1/2}$, it is more likely to be due to Si XI $2s2p^33P^0_{2s/2} - 2s2p^33S_{1/2}$ at $\lambda$ 170·6 should be too weak to be observed in the Sun, as is indeed the case.

(iii) Fe X $3s^23p^53P^0 - 3s^23p^43d^2$. $N(3P)/N_g$ may be calculated from $\Phi(3s^23p^43d^2)/\Phi(3s^23p^53P^0)$. It can be shown that $2P_{2s/2} - 2D_{3/2}$ is more likely to be due to Si XI $2s2p^33P^0_{2s/2} - 2s2p^33D_{3/2}$.

(iv) Fe XI $3s^23p^43P^0 - 3s^23p^43d^2$. $N(3P)/N_g$ may be calculated from $\Phi(3s^23p^43d^2)/\Phi(3s^23p^43P^0)$. Using this value and $\Phi(3s^23p^43P^0)/\Phi(3s^23p^43P^0)$, values of $N(3P)/N_g$ may be found.

(v) Fe XV $3s^21S - 3s3p^1P^0$ and $3s3p^3P^0 - 3s3d^3D$. The only unknown quantity in the expression for the relative intensity of $1S_0 - 1S_1P^0$, $\lambda 284·2$ and $1S_0 - 3P^0$, $\lambda 414$, is the oscillator strength of $1S_0 - 3P^0$. Using the observed relative intensities and relative cross-sections, a value of $f(1S_0 - 3P^0)$ = 0.18 is obtained. From $\Phi(3P^0)/\Phi(3P^0)$, a value of $N(3P^0)/N_g$ may be found.

The values of $N_g/N_e$ calculated using mean intensities are given in Table IV. The relative intensities of lines within a multiplet do not vary significantly between 1963 and 1964. The main source of error will be unsuspected blends, especially in weak lines.

4. The determination of abundance. The values of $N_u/N_e$ derived from the forbidden lines have been corrected for the integration over the line of sight, but still involve an integration of emission from heights above 5000 km. However, the ultra-violet line intensities also include an integration over heights above about 5000 km. It should, therefore, be valid to combine the values of $N_u/N_e$ and $N_u/N_g$, to give a value of $N_g/N_e$ for each ion. $N(ion)/N_g$ can be found from $N_u/N_g$, so that $N(ion)/N(H)$ may be calculated, assuming $N(H) = 0.8N_e$. The values of $N(ion)/N(H)$ are given in Table IV.

If the corona is isothermal over the region in which the ions under consideration are formed, then to find the abundance $N(Fe)/N(H)$, the values of the individual ion abundance can be simply added. Allowance must be made for ions that are unobserved but make a significant contribution. From Table IV the values of $N(Fe XI)/N(H)$ and $N(Fe XIV)/N(H)$ are $1.2 \times 10^{-5}$ and $8.2 \times 10^{-6}$ respectively, so that the values for $N(Fe XII)/N(H)$ and $N(Fe XIII)/N(H)$ will hardly be less than $1.0 \times 10^{-5}$. The total ion abundance is then

$$\frac{N(Fe)}{N(H)} = 5.7 \times 10^{-5}, \text{ or } \log \left( \frac{N(Fe)}{N(H)} \right) = -4.25.$$

The alternative approach is to consider each ion as being formed at the temperature where $N(ion)/N(Fe)$ is a maximum. There is evidence from observations of the widths of forbidden lines (Billings 29), that the Fe X and Fe XIV lines are formed in regions of different temperature. The values of $N(ion)/N(Fe)$ have been calculated over the temperature range of interest. The value of $N(ion)/N(H)$ for each ion can be combined with the value of $N(ion)/N(Fe)$ at $T_{max}$, to give the abundance $N(Fe)/N(H)$. The results, assuming that 70% of each ion is formed at $T_{max}$ (see section 3 (a)) are given in Table IV. The mean value, giving the Fe XV result half weight as there is uncertainty in the intensity of $3P^0 - 3D_3$, is $\log \left( \frac{N(Fe)}{N(H)} \right) = -4.30$. This
The abundance of iron in the solar corona

Table IV

<table>
<thead>
<tr>
<th>Ion</th>
<th>Upper Level</th>
<th>$N_{ll}/N_g$</th>
<th>$N_{ll}/N_e$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fe X</td>
<td>$^{2s}P_{1/2}$</td>
<td>0.022</td>
<td>$7 \times 10^{-7}$</td>
</tr>
<tr>
<td></td>
<td>$^{3s}P_{1/2}$</td>
<td>0.087</td>
<td>$2 \times 10^{-7}$</td>
</tr>
<tr>
<td>Fe XI</td>
<td>$^{2s}P_{1/2}$</td>
<td>0.14</td>
<td>$1 \times 10^{-7}$</td>
</tr>
<tr>
<td></td>
<td>$^{3s}P_{1/2}$</td>
<td>0.087</td>
<td>$6 \times 10^{-8}$</td>
</tr>
<tr>
<td>Fe XIV</td>
<td>$^{2s}P_{1/2}$</td>
<td>0.14</td>
<td>$1 \times 10^{-7}$</td>
</tr>
<tr>
<td></td>
<td>$^{3s}P_{1/2}$</td>
<td>0.087</td>
<td>$6 \times 10^{-8}$</td>
</tr>
</tbody>
</table>

Population ratio

<table>
<thead>
<tr>
<th>log $T_{max}$</th>
<th>($^\circ$K)</th>
<th>$N(Fe)/N(H)$</th>
<th>$N(Fe)/N(H)$ at $T_{max}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.18</td>
<td>1.5 $\times 10^{-4}$</td>
<td>6.7 $\times 10^{-5}$</td>
<td></td>
</tr>
<tr>
<td>6.18</td>
<td>1.2 $\times 10^{-4}$</td>
<td>5.9 $\times 10^{-5}$</td>
<td></td>
</tr>
<tr>
<td>6.36</td>
<td>8.2 $\times 10^{-5}$</td>
<td>4.2 $\times 10^{-5}$</td>
<td></td>
</tr>
<tr>
<td>6.44</td>
<td>1.2 $\times 10^{-5}$</td>
<td>5.9 $\times 10^{-5}$</td>
<td></td>
</tr>
</tbody>
</table>

Weighted mean: $5.9 \times 10^{-5}$
value is preferable to that obtained by the previous method, as it does not assume values of $N(\text{Fe} \text{ XII})/N(\text{Fe})$ and $N(\text{Fe} \text{ XIII})/N(\text{Fe})$.

If the corona is not isothermal the first method will tend to overestimate the abundance, and if the corona is isothermal the second method will tend to underestimate the abundance. Therefore the results of this investigation support the view that the abundance of iron in the solar corona is an order of magnitude greater than that found for the photosphere.

5. Excitation rates and the electron density. The processes populating an excited level of the ground term are as follows:

(i) direct collisional excitation by electrons; (ii) direct collisional excitation by protons; (iii) collisional excitations to higher terms followed by cascade; (iv) radiative excitation by photospheric radiation. Recombination to the excited level, directly or to higher levels followed by cascade is negligible compared to the above processes.

(i) The direct collisional transition rate coefficient is

$$C_{\text{nu}} = 6.25 \times 10^5 T_e^{1/2} \sigma_1 e^{-h\nu/kT} \text{ cm}^3 \text{s}^{-1}.$$ 

For Fe XIV Blaha (30) finds $\sigma_1 = 0.16 \times 10^{-17} \text{ cm}^2$. As this is the only value available, the same value will be used for Fe X and Fe XI.

(ii) Seaton (31) calculates that for Fe XIV, at $T=2 \times 10^6 \text{°K}$ the excitation rate for proton impacts is $C_{\text{proton}} = 1.20 \times 10^{-8} \text{cm}^3 \text{s}^{-1}$. It will be assumed that proton impact makes the same relative contribution in other ions at their respective $T_{e \text{ max}}$.

(iii) The process of collisional excitation to higher terms followed by cascade is important (Pecker & Thomas 32). The collisional excitation rate is that given by Van Regemorter but increased by a factor of 1.5 (see section 3 (a)). The necessary $f$-values have been calculated by the method of Bates & Damgaard (33), except for Fe XIV and $3s^23p^52P^0 - 3s3p^63S$ in Fe X, where Garstang's values have been used, and Fe XI $3s^23p^42P - 3s3p^53P$ where Varsavsky's (34) values have been used. The excitation potentials given in Table V for lines as yet unidentified are rough estimates by the present author.

(iv) The radiative excitation rate is given by

$$A_{\text{u}} = A_{\text{ud}} D(r)(e^{-h\nu/kT} - 1)^{-1}(\omega_{\text{ud}}/\omega_t) \text{ where } T_r = 6000 \text{°K}.$$ 

The radiative de-excitation rate $A_{\text{ud}} N_u$, less de-excitation by the reverse of process (iii), which in most cases is negligible, can then be equated to the sum of the excitation processes. Then

$$A_{\text{ud}} N_u = A_{\text{iu}} N_i + N_e N_g C_{\text{total}}$$

where the factor for de-excitation has been included in $C_{\text{total}}$. If $N_u/N_g$ is known, then the electron density, $N_e$, can be calculated. The calculations have been performed for Fe X, XI and XIV, and the excitation rates, $f$-values and values of $N_e$ are given in Table V.

Observations of the brightness of the corona at time of eclipse lead to electron densities between $2 \times 10^8 \text{ cm}^{-3}$ and $10^8 \text{ cm}^{-3}$, for heights of less than 10,000 km. Radio frequency observations give values in the same range (van de Hulst 35, de Jager 36). Thus the values of the electron density found in the present paper are within the range of values derived from other observations. From
Table V
Excitation rates and electron density

<table>
<thead>
<tr>
<th>Ion</th>
<th>Multiplet*</th>
<th>ΔJ</th>
<th>Upper level of ground term</th>
<th>f_{i→i}</th>
<th>W</th>
<th>T_{e}^{1/2}</th>
<th>C_{i→i}</th>
<th>f_{u→i}</th>
<th>( \sum f_{i} )</th>
<th>( C' ) no. reaching upper level</th>
<th>( A_{iu} )</th>
<th>( C_{total} )</th>
<th>( N_{e} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fe X</td>
<td>( 3s^23p^5 ) ( 3p^0 ) ( -3s3p^4 ) ( 3S )</td>
<td></td>
<td></td>
<td></td>
<td>3/2−1/2</td>
<td>2p_{1/2}</td>
<td>0'17</td>
<td>36</td>
<td>1'12 \times 10^8</td>
<td>3'70</td>
<td>0'31</td>
<td>1'14</td>
<td>0'31</td>
</tr>
<tr>
<td></td>
<td>( -3p^43d ) ( 3^2D )</td>
<td></td>
<td></td>
<td></td>
<td>3/2−3/2</td>
<td>2p_{1/2}</td>
<td>0'17</td>
<td>71</td>
<td>1'12 \times 10^8</td>
<td>0'82</td>
<td>0'83</td>
<td>0'68</td>
<td></td>
</tr>
<tr>
<td></td>
<td>( -3p^43d ) ( 2^P )</td>
<td></td>
<td></td>
<td></td>
<td>3/2−3/2</td>
<td>2p_{1/2}</td>
<td>0'66</td>
<td>70</td>
<td>1'12 \times 10^8</td>
<td>3'36</td>
<td>0'16</td>
<td>0'54</td>
<td></td>
</tr>
<tr>
<td></td>
<td>( -3p^43d ) ( 2^P )</td>
<td></td>
<td></td>
<td></td>
<td>3/2−1/2</td>
<td>2p_{1/2}</td>
<td>0'13</td>
<td>70</td>
<td>1'12 \times 10^8</td>
<td>0'66</td>
<td>0'67</td>
<td>0'44</td>
<td></td>
</tr>
<tr>
<td>Fe XI</td>
<td>( 3s^23p^4 ) ( 3p^0 ) ( -3s3p^4 ) ( 3P^0 )</td>
<td></td>
<td></td>
<td>3/2−1/2</td>
<td>2p_{1/2}</td>
<td>0'18</td>
<td>70</td>
<td>1'12 \times 10^8</td>
<td>0'91</td>
<td>0'34</td>
<td>0'31</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>( -3p^33d ) ( 3^2D^0 )</td>
<td></td>
<td></td>
<td>2−2</td>
<td>3p_{1/2}</td>
<td>0'32</td>
<td>35</td>
<td>1'22 \times 10^8</td>
<td>7'79</td>
<td>0'25</td>
<td>1'95</td>
<td>0'37</td>
<td>7'38</td>
</tr>
<tr>
<td></td>
<td>( -3p^33d ) ( 2^P^0 )</td>
<td></td>
<td></td>
<td>2−1</td>
<td>3p_{1/2}</td>
<td>0'11</td>
<td>35</td>
<td>1'22 \times 10^8</td>
<td>2'67</td>
<td>0'25</td>
<td>0'67</td>
<td></td>
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</tr>
<tr>
<td></td>
<td>( -3p^33d ) ( 3^2D^0 )</td>
<td></td>
<td></td>
<td>2−2</td>
<td>3p_{1/2}</td>
<td>0'19</td>
<td>70</td>
<td>1'23 \times 10^8</td>
<td>1'23</td>
<td>0'74</td>
<td>0'91</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>( -3p^33d ) ( 2^P^0 )</td>
<td></td>
<td></td>
<td>2−1</td>
<td>3p_{1/2}</td>
<td>0'01</td>
<td>70</td>
<td>1'23 \times 10^8</td>
<td>0'06</td>
<td>0'42</td>
<td>0'03</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>( -3p^33d ) ( 3^2S^0 )</td>
<td></td>
<td></td>
<td>2−2</td>
<td>3p_{1/2}</td>
<td>0'36</td>
<td>70</td>
<td>1'23 \times 10^8</td>
<td>2'31</td>
<td>0'25</td>
<td>0'58</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>( -3p^33d ) ( 3^2S^0 )</td>
<td></td>
<td></td>
<td>2−1</td>
<td>3p_{1/2}</td>
<td>0'12</td>
<td>70</td>
<td>1'23 \times 10^8</td>
<td>0'77</td>
<td>0'25</td>
<td>0'19</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fe XIV</td>
<td>( 3s^23p^4 ) ( 3p^0 ) ( -3s3p^4 ) ( 3P^0 )</td>
<td>1/2−1/2</td>
<td>2p_{1/2}</td>
<td>0'16</td>
<td>48</td>
<td>1'52 \times 10^8</td>
<td>2'31</td>
<td>0'61</td>
<td>0'41</td>
<td>0'59</td>
<td>7'15</td>
<td>1'09 \times 10^9</td>
<td></td>
</tr>
<tr>
<td></td>
<td>( -3s3p^4 ) ( 3S )</td>
<td>1/2−1/2</td>
<td>2p_{1/2}</td>
<td>0'18</td>
<td>49</td>
<td>1'52 \times 10^8</td>
<td>2'43</td>
<td>0'82</td>
<td>2'00</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>( -3s3p^4 ) ( 3D )</td>
<td>1/2−3/2</td>
<td>2p_{1/2}</td>
<td>0'21</td>
<td>46</td>
<td>1'52 \times 10^8</td>
<td>3'17</td>
<td>0'045</td>
<td>0'14</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>( -3s3p^4 ) ( 2D )</td>
<td>1/2−3/2</td>
<td>2p_{1/2}</td>
<td>0'075</td>
<td>36</td>
<td>1'52 \times 10^8</td>
<td>1'69</td>
<td>0'025</td>
<td>0'05</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>( -3d ) ( 2D )</td>
<td>1/2−3/2</td>
<td>2p_{1/2}</td>
<td>0'55</td>
<td>60</td>
<td>1'52 \times 10^8</td>
<td>5'23</td>
<td>0'21</td>
<td>1'10</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* \( 3^2D, 2^P, 3^2D^0, 3^2P^0 \) denote inclusion of terms from all possible parents.
observations made from the first Orbiting Solar Observatory (O.S.O - 1) Neupert (37), found that the ultra-violet lines of Fe XIV are associated with plage regions but to a lesser extent than the Fe XV line at \( \lambda 284 \). The value of \( N_e = 1.09 \times 10^9 \) from Fe XIV is probably representative of regions of activity rather than the quiet corona.

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References

(17) Burgess, A., unpublished.