THE 3s3p 2P-3s3p 4P INTERCOMBINATION LINES OF Fe xiv IN THE SUN

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ABSTRACT

We have examined EUV spectra of solar flares obtained with the Naval Research Laboratory’s S082A slitless spectrograph on board Skylab and provisionally identified the five components of the Fe xiv 3s3p 2P-3s3p 4P intercombination multiplet. A comparison of the observed Fe xiv line intensities with theoretical predictions reveals good agreement between theory and experiment, which tends to confirm our identifications and those made previously by Träbert, Hutton, and Martinson. The potential usefulness of the lines as electron density diagnostics is briefly discussed.

Subject headings: atomic processes — Sun: corona — Sun: flares — Sun: spectra — ultraviolet: spectra

1. INTRODUCTION

Emission lines arising from allowed transitions between the 3s3p 2P, 3s3p 2D, and 3s3p 2S states in Al-like Fe xiv have been frequently observed in the EUV spectra of both solar (Dere 1978; Widing & Doyle 1990) and laboratory (Davé et al. 1987) plasmas. Their usefulness as electron density diagnostics for the emitting plasma is well known, and several authors have calculated such diagnostics over the past few years (see, e.g., Blaha 1971; Mason 1975; Keenan et al. 1991). The Keenan et al. results are probably the most reliable currently available as they employ electron impact excitation rates determined using the R-matrix code (Dufton & Kingston 1991).

Recently Träbert, Hutton, & Martinson (1987) have identified several of the Fe xiv 3s3p 2P and 3s3p 2D intercombination transitions in beam-foil spectra covering the wavelength interval 400–600 Å, some of which [the (J–J') = (1/2–1/2), (3/2–3/2) and (3/2–5/2) components] coincided with unidentified features in Dere’s (1978) line list for solar flares. In this paper we reexamine the solar flare spectra to try and provisionally identify all of the Fe xiv intercombination transitions. We also compare the relative intensities of these lines with our theoretical predictions (Keenan et al. 1991) in order to confirm these identifications.

2. THEORETICAL RATIOS

The model ion adopted for Fe xiv has been discussed in detail by Keenan et al. (1991). Briefly, the six energetically lowest LS states were included in the calculation, namely 3s3p 2S, 3s3p 4P, 3s3p 2D, 3s3p 2P, and 3s3d 2D, making a total of 12 levels when the fine structure splitting in the doublet and quartet terms is included. Only collisional excitation and deexcitation by electrons and protons (the latter in the case of the 3s3p 2P 1/2→3s3p 2P 1/2 transition) and spontaneous radiative deexcitation processes were considered, and the plasma was assumed to be optically thin. Further details may be found in Keenan et al. (1991).

In Table 1 we list the theoretical emission-line ratios $R_1 = I(3s^23p^2P_{3/2}\rightarrow3s3p^2P_{5/2})/I(3s^23p^2P_{1/2}\rightarrow3s3p^2P_{1/2})$ and $R_2 = I(3s^23p^2P_{3/2}\rightarrow3s3p^2P_{5/2})/I(3s^23p^2P_{3/2}\rightarrow3s3p^2P_{3/2})$ as a function of electron density at the electron temperature of maximum Fe xiv fractional abundance in ionization equilibrium, log $T_{\text{e}}$ = 6.2 (Arnaud & Rothenflug 1985). However, these results are relatively insensitive to the adopted value of $T_{\text{e}}$, with $\sim 5\%$ changes in $R_1$ and $R_2$ at $N_e = 10^{12}$ cm$^{-3}$, which decrease to $\sim 5\%$ at $N_e = 10^{13}$ cm$^{-3}$. We note that the ratios $R_1 = I(3s^23p^2P_{3/2}\rightarrow3s3p^2P_{5/2})/I(3s^23p^2P_{3/2}\rightarrow3s3p^2P_{3/2})$ and $R_2 = I(3s^23p^2P_{3/2}\rightarrow3s3p^2P_{3/2})/I(3s^23p^2P_{3/2}\rightarrow3s3p^2P_{3/2})$ have the same density dependence due to common upper levels as $R_1$ and $R_2$, respectively, but with $R_1 = 2.83 \times R_2$.

3. OBSERVATIONAL DATA

The solar spectra analyzed in the present paper were obtained by the Naval Research Laboratory’s XUV slitless spectrograph (S082A) on board Skylab. This instrument covered the wavelength region 171–630 Å, with a maximum spectral resolution of $\sim 0.1$ Å and a spatial resolution of 2". It is discussed in detail by Tousey et al. (1977) and Dere (1978).

Using the wavelengths measured by Träbert et al. (1987), we have searched for the five components of the 3s3p 2P-3s3p 4P intercombination multiplet in the sharp-line spectrum of the solar flare of 1973 June 15 at 14:27:40 UT midexposure (discussed in detail by Widing & Feldman 1989 and Widing & Cheng 1974), and in the bright, compact flare of 1973 August 9 at 15:55:15 UT (Dere et al. 1979; Dere & Cook 1979). In all cases emission features were identified and their wavelengths measured. These are summarized in Table 2, together with the wavelengths and identifications given by Träbert et al. from beam-foil spectra, plus the provisional solar identifications made by these authors on the basis of the S082A line list of Dere (1978). An inspection of the table reveals that we have now provisionally identified all five of the Fe xiv inter-
combination transitions in the solar spectrum, including the previously undetected $2_{P_{1/2}}-4_{P_{1/2}}$ and $2_{P_{3/2}}-4_{P_{3/2}}$ line ratios $R_1$ and $R_2$, respectively. The solar wavelengths should be much more reliable than the beam-foil measurements, as the estimated errors for the former are $\pm 0.03 \, \text{Å}$ compared with approximately $\pm 0.3 \, \text{Å}$ for the latter.

As well as wavelengths, the relative emission-line strengths for the Fe xiv intercombination transitions were also measured. These are summarized in Table 3 for the emission-line ratios $R_1 = I(338.27 \, \text{Å})/I(444.26 \, \text{Å})$, $R_2 = I(338.27 \, \text{Å})/I(467.39 \, \text{Å})$, $R_3 = I(447.37 \, \text{Å})/I(484.86 \, \text{Å})$, and $R_4 = I(447.37 \, \text{Å})/I(429.54 \, \text{Å})$. The numbering of the ratios follows that given in § 2 and assumes that the identifications of Träbert et al. (1987) are correct. We considered the following flare events: 1973 June 15 at 14:27:40 UT mid-exposure and its associated active region (see Widing & Feldman 1989), 1973 August 9 at 15:55:15 UT (Dere et al. 1979; Dere & Cook 1979), and 1973 December 17 at 00:48:54 UT (Widing & Spicer 1980; Widing & Cook 1987). For the December 17 flare we have given line ratios measured in two different bright kernel features of the flare. The listed ratios should be accurate in most cases to approximately $\pm 30\%$ (Keenan et al. 1984; Widing, Feldman, & Bhatia 1986).
where the 484.86 Å line is even weaker on the tracing than the 429.54 Å transition.

The overall good agreement between theory and observation confirms both that the emission lines are from the Fe xiv intercombination multiplet and that they have been assigned to the correct fine-structure transitions. In addition, the results provide support for the accuracy of the atomic data used to calculate the theoretical emission-line ratios.

Finally, we note that an inspection of Table 1 reveals that \( R_1 - R_4 \) are quite sensitive to variations in the electron density. For example, \( R_1 \) varies by a factor of 2.7 between \( N_e = 10^9 \) and \( 10^{11} \) cm\(^{-3}\), while \( R_2 \) changes by a factor of 2 over the same density interval. Coupled with the wavelength proximity of the transitions involved, this implies that \( R_1 - R_4 \) are potentially useful \( N_e \)-diagnostics for intermediate density solar features (such as active regions), provided the ratios can be measured accurately. This should be possible using, for example, the Coronal Diagnostic Spectrometer on board the SOHO mission (Harrison 1990).

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**REFERENCES**


**TABLE 4**

**PREDICTED Fe xiv EMISSION-LINE RATIOS FOR \( \log T_e = 6.2 \)**

<table>
<thead>
<tr>
<th>Solar Feature</th>
<th>Adopted log ( N_e )^a</th>
<th>( R_1 )</th>
<th>( R_2 )</th>
<th>( R_3 )</th>
<th>( R_4 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Active region</td>
<td>9.6</td>
<td>1.9</td>
<td>1.2</td>
<td>5.3</td>
<td>12.0</td>
</tr>
<tr>
<td>1973 June 15 flare, 14:27:40 UT</td>
<td>10.3</td>
<td>2.9</td>
<td>1.7</td>
<td>8.2</td>
<td>16.0</td>
</tr>
<tr>
<td>1973 August 9 flare, 15:55:15 UT</td>
<td>10.3</td>
<td>2.9</td>
<td>1.7</td>
<td>8.2</td>
<td>16.0</td>
</tr>
<tr>
<td>1973 December 17 flare, 00:48:54 UT</td>
<td>10.7</td>
<td>3.3</td>
<td>1.8</td>
<td>9.3</td>
<td>17.4</td>
</tr>
</tbody>
</table>

^a Determined from the \( I(338.27\,\AA)/I(364.47\,\AA) \) and \( I(338.27\,\AA)/I(352.10\,\AA) \) emission-line ratios in Fe xii (see Tayal et al. 1989), apart from the active region where log \( N_e \) has been estimated from allowed line ratios in Fe xiv (Keenan et al. 1991).