ELECTRON DENSITY DIAGNOSTICS FOR Fe xii IN THE SOLAR PLASMA

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ABSTRACT

We have calculated density-sensitive emission-line ratios \( R_1 = I(338.27 \text{ Å})/I(364.47 \text{ Å}) \) and \( R_2 = I(338.27 \text{ Å})/I(352.10 \text{ Å}) \) for Fe xii using new electron collisional excitation rates which are substantially larger than those previously published. Electron densities deduced from the observed values of \( R_1 \) and \( R_2 \) for solar active region and flares obtained by the NRL SO82A slitless spectrograph on board Skylab are in good agreement. The electron densities also compare well with those obtained from Fe xiii and Fe xiv, which are formed at electron temperatures similar to that of Fe xii.

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

I. INTRODUCTION

Accurate atomic data such as excitation energies, oscillator strengths for dipole allowed and intercombination transitions, and electron collisional excitation rates for all the fine-structure transitions among the terms of ground \( 3s^23p^3 \) configuration and between the terms of ground \( 3s^23p^3 \) and first excited \( 3s3p^4 \) configurations in Fe xii have recently been reported (Tayal and Henry 1986, 1988; Tayal, Henry, and Pradhan 1987). These atomic data can be used for an accurate interpretation of large amounts of observational data which have been collected by the Naval Research Laboratory (NRL) Skylab experiments (Feldman and Doschek 1977; Cohen, Feldman, and Doschek 1978; Dere et al 1979). In the calculation of the new atomic data the important electron correlations, relativistic interactions, and resonance effects are properly taken into account. At low electron energies, the Rydberg series of resonances are found to make significant enhancements in the total collision strengths.

Transitions among the fine-structure terms of the ground \( 3s^23p^3 \) configuration in Fe xii give rise to forbidden lines in the UV spectral region, while the allowed and intercombination lines in the XUV spectral region arise due to the transitions between the ground and first two excited \( 3s3p^4 \) and \( 3s^23p^23d \) configurations in Fe xii. The UV forbidden lines (1175–1940 Å) and XUV allowed lines (171–630 Å) have been observed in the sun by the NRL Skylab slit spectrograph and spectroheliograph, respectively. The wavelengths of these Fe xii solar emission lines have been accurately measured by Feldman and Doschek (1977), Sandlin, Brueckner, and Tousey (1977), and Behring et al. (1976). The ratio of the intensities of emission lines provides a useful technique to determine the physical conditions of the emitting plasma. Several Fe xii emission lines intensity ratios belonging to UV and XUV spectral region have been considered in the past to infer electron density of solar corona and flares. Gabriel and Jordan (1975), and Feldman, Cohen, and Doschek (1983) have discussed the use of various forbidden line ratios in Fe xii to determine electron density in the quiet and active regions of solar corona. Flower (1977), Kastner and Mason (1978), Dere et al. (1979), and Feldman, Cohen, and Doschek (1983) calculated theoretical intensity ratios for the UV lines of Fe xii using atomic data of Flower (1977) and Bromage, Cowan, and Fawcett (1978). The populations of the excited levels of the ground \( 3s^23p^3 \) configuration calculated with Flower's atomic data were significantly underestimated. Flower included the resonance contributions in the total collision strengths in an approximate way using the method described by Petrin (1970) and assumed the collision strengths to be independent of energy. Recently Tayal and Henry (1988) calculated the relative level populations and emission-line strengths for the forbidden lines of Fe xii using the new atomic data reported by Tayal and Henry (1986), Tayal, Henry, and Pradhan (1987), and Tayal and Henry (1988). The populations of the excited levels obtained by Tayal and Henry (1988) are significantly larger than those obtained with the Flower atomic data. In this paper, we extend the work of Tayal and Henry (1988) to describe the electron density sensitivity of XUV spectral lines to obtain density estimates in a variety of solar features.

II. ATOMIC DATA

The theoretical intensity ratios can be calculated by solving the steady state rate equations including all the important radiative and collisional processes. We have used recently published atomic data in the present level population and line strength calculations. The model ion for Fe xii consisted of 29 fine-structure levels with \( 3s^23p^4 \), \( 3s3p^4 \), and \( 3s^23p^23d \) configurations. In our calculation, energies of all these levels are taken from Cordis and Sugar (1982). The oscillator strengths for electric dipole allowed and intercombination transitions among the 19 fine-structure levels are reported by Tayal and Henry (1986). In the calculation of oscillator strengths, all the levels were represented by extensive configuration-interaction (CI) wave functions and the relativistic effects were incorporated by means of the Breit-Pauli Hamiltonian. The oscillator strengths for intercombination transitions were found to be sensitive to the CI effects. The other radiative data were taken...
Electron impact excitation rates for several transitions among the lowest 13 fine-structure terms of the 3s3p3p and 3s3p configurations were published by Tayal, Henry, and Pradhan (1977), and Tayal and Henry (1988). In these calculations, the lowest seven LS target states 3s2p23P0, 3s3p23D0, 3p34P0, 3p34S0, 3p32P and 3p32D were included in the close-coupling expansion of the total wave function. These target states were represented by CI wave functions. The reactance matrices obtained in the non-relativistic calculations were recoupled in an intermediate coupling scheme to obtain the total collision strengths for fine-structure transitions using term-coupling coefficients which accounted for the relativistic effects in the target. Rydberg series of resonances converging to different excitation thresholds were found to dominate the cross sections for several transitions at low electron energies. The details of the new atomic data calculation can be found in Tayal, Henry, and Pradhan (1987) and Tayal and Henry (1988). The electron collisional excitation rates for the transitions between the fine-structure levels of 3s3p3p and 3s3p3d configurations were calculated from the collision strengths of Flower (1977). The effect of proton excitation on level populations in Fe xii is negligible (Feldman, Cohen, and Doschek 1983; Flower 1977).

III. OBSERVATIONAL DATA

The 3s2p3 2D5/2, 3p34S0, 3p32P, and 3s2p3 5P0, 3s3p23D0, 3p34P, 3p32D, 3P, and 3s were included in the close-coupling expansion of the total wave function. These target states were represented by CI wave functions. The reactance matrices obtained in the non-relativistic calculations were recoupled in an intermediate coupling scheme to obtain the total collision strengths for fine-structure transitions using term-coupling coefficients which accounted for the relativistic effects in the target. Rydberg series of resonances converging to different excitation thresholds were found to dominate the cross sections for several transitions at low electron energies. The details of the new atomic data calculation can be found in Tayal, Henry, and Pradhan (1987) and Tayal and Henry (1988). The electron collisional excitation rates for the transitions between the fine-structure levels of 3s3p3p and 3s3p3d configurations were calculated from the collision strengths of Flower (1977). The effect of proton excitation on level populations in Fe xii is negligible (Feldman, Cohen, and Doschek 1983; Flower 1977).

IV. RESULTS AND DISCUSSION

For optically thin plasmas, the emission-line strengths can be obtained from the line emissivitiies and the physical dimensions of the plasma. The line emissivitiies are derived from the level populations and the Einstein A-coefficients. The plasma dimensions can be eliminated by considering the emission line strength ratios. The level populations are determined by solving the steady state rate equations. We used the atomic data discussed in § II in these calculations. In Figure 1, we have plotted the theoretical Fe xii emission line ratio

\[ R_1 = \frac{I(3s2p3 2D5/2, 3p34S0, 3p32P)}{I(3s3p23D0, 3p34P, 3p32D, 3P, 3s))} \]

as a function of electron density at the temperature of maximum Fe xii abundance in ionization equilibrium, log \( T_{\text{max}} = 6.2 \) (Arnaud and Rothenflug 1985). We have also shown in this figure the theoretical line intensity ratio obtained by Dere et al (1979) using the distorted-wave data of Flower (1977). The present results are shown by the solid curve, while the results of Dere et al are shown by the dashed curve. The present line ratio results for differ by up to 20% from those of Dere et al (1979). This discrepancy between the two sets of results can mainly be attributed to the difference in atomic data used in the calculations. In Figure 2, we have shown the present theoretical emission line ratio

\[ R_2 = \frac{I(3s2p3 2D5/2, 3p34S0, 3p32P)}{I(3s3p23D0, 3p34P, 3p32D, 3P, 3s))} \]

as a function of electron density at the temperature of

<table>
<thead>
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<th>Solar Feature</th>
<th>( R_1 )</th>
<th>( R_2 )</th>
<th>( \log N_e(R_1) )</th>
<th>( \log N_e(R_2) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1973 Jun 15 flare, 14:27:13 UT</td>
<td>0.56</td>
<td>0.95</td>
<td>10.5</td>
<td>10.7</td>
</tr>
<tr>
<td>1973 Jun 15 flare, 14:27:40 UT</td>
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<td>0.75</td>
<td>10.2</td>
<td>10.4</td>
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<tr>
<td>1973 Aug 9 flare, 15:55:15 UT</td>
<td>0.50</td>
<td>...</td>
<td>10.3</td>
<td>...</td>
</tr>
<tr>
<td>1973 Dec 17 flare, 00:48:54 UT</td>
<td>0.69</td>
<td>0.97</td>
<td>10.7</td>
<td>10.7</td>
</tr>
<tr>
<td>Active region McMath 12375</td>
<td>0.31</td>
<td>0.50</td>
<td>9.7</td>
<td>9.9</td>
</tr>
<tr>
<td>Active region McMath 12390</td>
<td>0.43</td>
<td>0.75</td>
<td>10.1</td>
<td>10.4</td>
</tr>
</tbody>
</table>

Solving the steady state rate equations. We used the atomic data discussed in § II in these calculations. In Figure 1, we have plotted the theoretical Fe xii emission line ratio

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Fig. 2.—The theoretical emission-line ratio \( R_2 = \frac{I(3s^23p^1P - 3s3p^*3/2)}{I(3s^23p^1P - 3s3p^*3/2 - 3p^1P)} \) plotted as a function of electron density at the temperature of maximum Fe xii abundance in ionization equilibrium, \( \log T_{\text{max}} = 6.2 \) (Arnaud and Rothenflug 1985).

maximum Fe xii abundance in ionization equilibrium. It is clear from Figures 1 and 2 that the ratios \( R_1 \) and \( R_2 \) are very sensitive to electron density. In Table 1, the curves of Figures 1 and 2 are applied to the observed intensity ratios to obtain electron densities. It may be seen from Table 1 that the electron densities derived from the observed values of \( R_1 \) and \( R_2 \) are in good agreement with each other. Furthermore, Fe xii electron densities in Table 1 compare favorably with those deduced from line ratios of ions formed at similar electron temperatures. For example, Widing and Spicer (1980) find \( \log N_e = 10.5 \) for 1973 December 17 flare from Fe xiv (\( \log T_{\text{max}} = 6.3 \); Arnaud and Rothenflug 1985), while for active region McMath 12375, Dere (1982) finds \( \log N_e = 9.6 \) from Fe xii (\( \log T_{\text{max}} = 6.2 \); Arnaud and Rothenflug 1985). These results provide observational support for the accuracy of the atomic data used in the present calculations.

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