DIAGNOSTIC LINE RATIOS FOR HIGHLY IONIZED IONS OF THE BERYLLIUM ISOELECTRONIC SEQUENCE AND A COMPARISON WITH SOLAR OBSERVATIONAL DATA

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To cite this version:

HAL Id: jpa-00229360
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Submitted on 1 Jan 1989

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Abstract: Observations of the relative line strengths of Beryllium like ions in a high temperature plasma can be used to derive the electron temperature and density of the emitting region through diagnostic line ratios \([1,2]\). However, to calculate such ratios reliably, accurate atomic data must be employed, especially for the electron impact excitation rates of the relevant transitions \([3]\). In this paper we compare the theoretical S \(\text{XI}\) and Ar \(\text{XV}\) emission line ratios \(R_1 = I(2s2p ^3P - 2s^2P) / I(2s2p ^3P_1 - 2s^2P_1)\), and \(R_2 = I(2s2p ^3P - 2s^2P) / I(2p^3 P_2 - 2s2p^3P_2)\) with observational data for several solar flares, obtained using the SO82A instrument on board Skylab. Good agreement is found between theory and observation for \(R_1\) for both ions, which provides support for the electron impact excitation rates adopted in the calculations. However, in the case of \(R_2\), all the observed values for S \(\text{XI}\) and Ar \(\text{XV}\) are much smaller than the theoretical estimates, which is probably due to blending in the \(2p^3 P_2 - 2s2p^3P_2\) lines.

1. Introduction

The atomic transitions within the \(n=2\) complex of moderately high \(z\) elements in the beryllium isoelectronic series emit in the ultraviolet region. These lines are observed in high temperature (\(T=10^7\) K) laboratory and astrophysical plasmas. Observations of the relative strengths of these lines in a given ion can be used to derive the electron density and temperature of the emitting region. In order to determine reliable theoretical line ratios, accurate atomic data must be employed, especially for oscillator strengths and electron excitation rates \([3]\). Electron excitation rates have been determined at Queen's University Belfast using the \(R\)-matrix code \([4-9]\). An interpolation of these rates has been made recently by Keenan \([10]\). In this paper we use these interpolated results to derive diagnostic line ratio for S \(\text{XI}\) and Ar \(\text{XV}\) and compare them with observational data for solar flares obtained with the NRL slitless spectrograph, on board Skylab.

2. Theoretical Ratios

The same model was adopted for S \(\text{XI}\) and Ar \(\text{XV}\). Briefly, it consisted of the six energetically lowest \(LS\) states \(2s^3P\), \(2s2p\ ^3P\), \(^1P\), \(2p^2\ ^3P\), \(^1D\), and \(^1S\) which makes a total of ten levels after fine structure splitting is taken into account. Energies of all the ionic levels were taken from Fawcett \([11]\). The electron impact excitation rates were taken from an interpolation by Keenan \([10]\). For S \(\text{XI}\), most of the Einstein A-coefficients were taken from Muhlethaler and Nussbaumer \([12]\), whereas for Ar \(\text{XV}\), in general, the values of Bhatia, Feldman and Seeley \([13]\) were adopted, except for the transitions \(2s2p\ ^3P_2 - 2p^2\ ^1S\) and \(2p^2\ ^1S - 2s2p\ ^3P_2\), which were taken from Shorer and Lin \([14]\), and \(2s2p\ ^3P_2 - 2s2p\ ^3P_1\) from Tunnell and Bhalla \([15]\). Proton rates, which are only important for the fine structure transitions within the \(2p^3 P\) terms \([16,17]\) were obtained from Doyle \([18]\). It was noted by Doyle, Kingston and Reid \([17]\) that proton collisions among the \(2p^2\ ^3P\) levels are a negligible population mechanism compared with electron excitation from the \(2s2p\ ^3P\) levels and radiative transitions to other states and hence the former have not been included in our calculations.
The above atomic data was used in conjunction with the statistical equilibrium code of Dufton [18] and relative level populations for S XIII and Ar XV were calculated for a range of electron temperature and density. The emission line ratios $R$ (in energy units) can be derived from these level populations through the expression

$$R = \frac{I(λ_{ij})}{I(λ_{mn})} = \frac{N_j/N_n \cdot A_{ji}/A_{mn} \cdot λ_{mn}/λ_{ij}}{[19]}$$

where $N_j$ and $N_n$ are the upper level populations of the relevant transitions, $λ_{ij}$ and $λ_{mn}$ are the wavelengths of the lines and $A_{ji}$ and $A_{mn}$ are the Einstein A-coefficients. In figures 1 and 2 the emission line ratio $R_1$ ($=I(2p^2 1P - 2s^2 1S)/I(2s2p 3P_2 - 2s^2 1S)$ is plotted as a function of the temperature for S XIII and Ar XV respectively. In figures 3 and 4 we plot the emission line ratio $R_2$ ($=I(2p^2 1P - 2s^2 1S)/I(2p^2 3P_2 - 2s2p 3P_2)$ as a function of electron density.

3. Observational Data

The Naval Research Laboratory's xuv slitless grating spectroheliograph (SO82A) on board Skylab photographed dispersed images of the sun in many spectral lines between 171 to 630 Å. A spatial resolution of 2 arc seconds was obtained on the grating normal, and the maximum spectral resolution 0.1 Å [20,21,22]. The $2s2p 1P - 2s^2 1S, 2p^2 3P_2 - 2s2p 3P_2$ and $2s2p^3P_1 - 2s^2 1S$ emission lines in S XIII have been observed in solar flare spectra at 256.70 Å, 308.96 Å, and 491.46 Å respectively and at wavelengths of 221.12 Å, 266.23 Å, and 423.8 Å in Ar XV. The entire wavelength region (171 - 630 Å) was covered in two wavelength ranges by changing the position of the grating. The lines for $R_2$ were observed simultaneously but for the ratio $R_1$ the lines were taken from both short and long wavelength plates, hence light curves had to be used to take the intensity time dependence into account [23,24].

4. Results and Discussions

In table 1 we list the observed values of the S XIII temperature sensitive ratio $R_1 = I(256.98)/I(491.45)$ and the density sensitive ratio $R_2 = (256.98)/I(308.96)$ for the solar flares of August 9, 1973 discussed in detail by Dere [21], and Dere and Cook [22] December 9, 1973 [23,25] and January 21, 1974 (unpublished observations). In table 2 there is a list of the same ratios $R_1 = I(221.12)/I(423.98)$ and $R_2 = (221.12)/I(266.23)$ from the same sources.

A comparison between the theoretical S XIII emission line ratio $R_1 = I(2s2p 1P - 2s^2 1S)/I(2s2p^3P_1 - 2s^2 1S)$ (figure 1) with observational data for several solar flares, obtained using the SO82A instrument on board Skylab gives agreement to within 20 % from figure 2 the value of the $R_1$ for Ar XV at the temperature of maximum fractional abundance for this ion ($log T_{max} = 6.5$) [26] is 47.5 which is also within 20 % of the observed values (table 2). This provides support for the electron impact excitation rates adopted in the present calculations, as both the resonant and intercombination lines are in the coronal approximation due to their large $A$-values, and hence depend on the ratio of the electron impact excitation rates [27]. In the case of the $R_2$ ratio in S XIII and Ar XV the observational data all lie below (figures 3 and 4) which is inconsistent with the values of $10^{11}$ cm$^{-3}$ derived from the Ca XVII line strengths in the same flares. This is similar to the results of Dufton et al. [28] who found the $R_2$ ratios in Ca XVII to be much smaller than the theoretical estimates (factors of approximately 2.5) than the theoretical estimates. Dufton et al. [28] considered several possible sources of the observed discrepancies, which also apply to the present analyses of S XIII and Ar XV. These include errors in the atomic data, the validity of a ten level model ion, optical depth effects, and errors in the SO82A instrument sensitivity curve. The conclusion reached was that all these explanations were unlikely. Further details of the procedures involved and the approximations made may be found in Dufton [18], Dufton et al. [28] and Keenan [29]. One remaining possibility is that there is for S XIII and Ar XV are much smaller than the theoretical blending in the $2p^2 3P_2 - 2s2p 3P_2$ lines.

We are unable, at this time, to suggest a blend for the S XIII 308.96 Å line but for the corresponding Ar XV line one blend that we have considered is that of N V at 266.19 Å, which may be present in the August 9 spectrum on plate 2A-027. We note that good agreement
between theory and observation was found by Lippmann et al. [30] and Huang et al. [31] for $R_2$ in Ca XVII, using tokamak laboratory spectra. Lippmann et al. [32] identified a feature at 232.9 Å due to the $3d^3D - 3p^1P$ transition in Ni XIX which could blend with the $2p^23P_2$ transition in Ca XVII at 232.96 Å. Observations of Ar XV in laboratory plasmas would therefore be of great interest to investigate the possibility of blending in the 308.96 Å line of S XIII and the Ar XV 266.23 Å line.

Acknowledgements

We would like to thank Prof. H.B. Gilbody and Dr. R.W.P McWhirter for their continued interest in this work. S.M.M. and F.P.K. are grateful to the SERC for financial support. This work was supported by NATO travel grant 0469/87.

References

11. Fawcett, B. C. Atomic Data Nucl. Data Tables 16, 135 (1975)

**TABLE 1.** OBSERVED S XI11 INTENSITY LINE RATIOS $R [I(\lambda_1)/I(\lambda_2)]$ IN SOLAR FLARES.

<table>
<thead>
<tr>
<th>SOLAR FLARE</th>
<th>PLATE NUMBER(S)</th>
<th>$\lambda_1$</th>
<th>$\lambda_2$</th>
<th>log R</th>
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<td>256.68</td>
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<td>308.96</td>
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<tr>
<td>17 DECEMBER 1973</td>
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<td>256.68</td>
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<tr>
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<td>308.96</td>
<td>0.81</td>
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**TABLE 2.** OBSERVED Ar XV INTENSITY LINE RATIOS $R [I(\lambda_1)/I(\lambda_2)]$ IN SOLAR FLARES.

<table>
<thead>
<tr>
<th>SOLAR FLARE</th>
<th>PLATE NUMBER(S)</th>
<th>$\lambda_1$</th>
<th>$\lambda_2$</th>
<th>log R</th>
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<td>221.12</td>
<td>266.23</td>
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<td>21 JANUARY 1974</td>
<td>3A-470</td>
<td>221.12</td>
<td>266.23</td>
<td>1.34</td>
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Figure 1: The theoretical Si XI temperature sensitive emission line ratio 
$R_t = \frac{I(2s2p^1P - 2s^2^1S)}{2s2p^3P_1 - 2s^2^1S}$ is plotted as a function of temperature.

Figure 2: The theoretical AR XV temperature sensitive emission line ratio 
$R_1 = \frac{I(2s2p^1P - 2s^2^1S)}{2s2p^3P_1 - 2s^2^1S}$ is plotted as a function of temperature.
Figure 3: The theoretical S XI11 emission line ratio $R_2 = \frac{I(2s2p\; ^1P - 2s^2\; ^1S)}{I(2p^2\; ^3P_2 - 2s2p\; ^3P_2)}$ is plotted as a function of electron density. The results are given for three temperatures: — — — log $T = 6.1$; log $T = 6.4$; and -0-0-0-0- log $T = 6.7$

Figure 4: The theoretical Ar XV emission line ratio $R_2 = \frac{I(2s2p\; ^1P - 2s^2\; ^1S)}{I(2p^2\; ^3P_2 - 2s2p\; ^3P_2)}$ is plotted as a function of electron density. The results are given for three temperatures: — — — log $T = 6.2$; log $T = 6.5$; and -0-0-0-0- log $T = 6.8$