A COMPARISON OF THEORETICAL LINE STRENGTHS FOR THE $2s^22p^2 - 2s2p^3$ TRANSITIONS IN Ne V WITH SOLAR DATA

F. P. KEENAN
Department of Pure and Applied Physics, The Queen's University of Belfast, Belfast BT7 1NN, N. Ireland

and

K. M. AGGARWAL
Department of Physics and Astrophysics, The University of Delhi, Delhi 110007, India

(Received in revised form 7 December, 1988)

Abstract. Results are presented for several theoretical line ratios in Ne V involving transitions between multiplets in the $2s^22p^2$ and $2s2p^3$ configurations. A comparison of these with solar data from the S082A and S-055 instruments on board Skylab reveals generally good agreement between theory and experiment, especially in the case of the high-resolution (S082A) observations. However the $2s^22p^2 1D - 2s2p^3 1P$ (365.6 Å) and $2s^22p^2 3P - 2s2p^3 3S$ (359 Å) lines appear to be blended, possibly with transitions in Fe X and Fe XI/Fe XIII, respectively. We note that the intensity ratio $I(365.6 \text{ Å})/I(416.2 \text{ Å})$ should be a valuable calibration check for a high-resolution ultraviolet instrument in the spectral range 360–420 Å.

1. Introduction

Emission lines arising from transitions in ions of the carbon isoelectronic sequence are frequently observed in the spectra of astrophysical objects, such as planetary nebulae (Aller and Keyes, 1987) and the solar corona (Widing and Cook, 1987), as well as in laboratory plasmas (Stratton et al., 1987). They may be used to derive the electron temperature ($T_e$) and density ($N_e$) of the emitting region through diagnostic line ratios, as discussed by, for example, Czyzak, Keyes, and Aller (1986) and Dere et al. (1979). However, to calculate reliable theoretical ratios, accurate atomic data must be employed, especially for $f$-values and electron impact excitation rates (Dufton and Kingston, 1981).

For a number of years Aggarwal and co-workers (see Aggarwal, Berrington, and Keenan, 1989, and references therein) have been involved in an extensive series of calculations of electron impact excitation rates for transitions in carbon-like O III, Ne V, Mg VII, Si IX, and Ca XV, with the R-matrix code (Burke and Robb, 1975; Berrington et al., 1978). Subsequently these results have been used to derive diagnostic line ratios for gaseous nebulae (Keenan and Aggarwal, 1987), late-type stellar atmospheres (Keenan et al., 1988a), the Sun (Keenan et al., 1986, 1988b) and laboratory plasmas (Keenan, Aggarwal, and Berrington, 1988).

Recently, Keenan, Aggarwal, and Widing (1986) have employed the above electron excitation rates in line ratio calculations involving the $2s^22p^2 1D - 2s2p^3 1D$, $2s2p^2 3P_2 - 2s2p^3 3D_3$ and $2s^22p^2 3P_1 - 2s2p^3 3D_2$ transitions in Ne V. These were
found to be quite $T_e$-sensitive, and, furthermore, were in good agreement with solar observations from the S082A spectrograph on board Skylab. In this paper we use the Ne v atomic data to determine theoretical line strengths for many $2s^22p^2 - 2s2p^3$ lines, and compare these with solar observational data from both the Skylab S082A and S-055 instruments.

2. Theoretical Ratios

Level populations for a wide range of electron temperatures and densities have been published for Ne v by Aggarwal (1986). Briefly, the model ion consisted of the lowest nine LS states, i.e., $2s^22p^2 \, 3P, 1D, 1S; 2s2p^3 \, 5S^0, 3D^0, 3P^0, 1D^0, 3S^0$, and $1P^0$, leading to fifteen levels when the splitting in the triplet terms was taken into account. Collisional excitation and de-excitation by electrons and spontaneous radiative de-excitation were the only atomic processes considered in the calculation, and the plasma was assumed to be optically thin. Further details may be found in Aggarwal (1986).

As noted by, for example, Keenan and Norrington (1987), level populations may be used to derive emission line ratios $R$ through the expression

$$ R = \frac{I(\lambda_{ij})}{I(\lambda_{mn})} = \frac{N_j}{N_n} \frac{A_{ji}}{A_{nm}} \frac{\lambda_{mn}}{\lambda_{ij}}, \quad (1) $$

where $\lambda_{ij}$, $\lambda_{mn}$, and $I(\lambda_{ij})$, $I(\lambda_{mn})$ are the wavelengths and intensities (in energy units) of the lines, respectively, $N_j$ and $N_n$ are the upper level populations of the relevant transitions and $A_{ji}$ and $A_{nm}$ are the Einstein $A$-coefficients. In Figures 1 and 2 we use the Ne v level populations and $A$-values listed in Aggarwal (1986) to plot the emission line ratios $R_1 = I(1D - 1P^0)/I(1D - 1D^0)$, $R_2 = I(3P - 3P^0)/I(1D - 1D^0)$, $R_3 = I(3P - 3D^0)/I(1D - 1D^0)$, $R_4 = I(1S - 1P^0)/I(1D - 1D^0)$ and $R_5 = I(3P - 3S^0)/I(1D - 1D^0)$ as a function of electron temperature for a range of $T_e$ about that of maximum Ne v fractional abundance in ionisation equilibrium, $\log T_e = \log T_{max} = 5.5$ (Arnaud and Rothenflug, 1985). The calculations in the figures were performed for an electron density of $10^{10}$ cm$^{-3}$, although we note that the line ratios are density insensitive for $N_e > 10^9$ cm$^{-3}$ (Aggarwal, 1986; Keenan, Aggarwal, and Widing, 1986).

An inspection of Figures 1 and 2 reveals that several of the ratios are quite sensitive to variations in the electron temperature and, hence, may be useful as $T_e$ diagnostics. For example, $R_2$ and $R_3$ vary by approximately factors of 1.9 and 3.1, respectively, between $\log T_e = 5.0$ and 6.0.

3. Observational Data

Many $2s^22p^2 - 2s2p^3$ transitions in Ne v, including $3P - 3S^0$, $1D - 1P^0$, $1D - 1D^0$, $1S - 1P^0$, $3P - 3P^0$, and $3P - 3D^0$ have been observed in solar spectra at wavelengths of 359, 365.6, 416.2, 416.8, 482, and 570 Å, respectively, by the Naval Research Laboratory's XUV slitless spectrograph (S082A) on board Skylab (Widing, Feldman,
Fig. 1. Theoretical NeV emission line ratios plotted as a function of electron temperature at an electron density of $N_e = 10^{10}$ cm$^{-3}$, with: solid line: $R_1 = I(^1D - ^3P^0)/I(^1D - ^1D^0) = I(365.6 \text{ Å})/I(416.2 \text{ Å})$; dashed line: $R_2 = I(^1S - ^1P^0)/I(^1D - ^1D^0) = I(416.8 \text{ Å})/I(416.2 \text{ Å})$; dashed-dot line: $R_3 = I(^3P - ^3S^0)/I(^1D - ^1D^0) = I(359 \text{ Å})/I(416.2 \text{ Å})$.

and Bhatia, 1986). This instrument covered the wavelength region 171–630 Å, with a spatial resolution of 2 arc sec and a spectral resolution of ~0.1 Å. It is discussed in detail by Tousey et al. (1977) and Dere (1978). The $^3P - ^3S^0$ (359 Å), $^1D - ^1D^0$ (416.2 Å), $^3P - ^3P^0$ (482 Å), and $^3P - ^3D^0$ (570 Å) lines have also been detected in solar spectra obtained with the Skylab Harvard S-055 EUV spectrometer (Noyes et al., 1985). A spatial area of 5 × 5 arc sec was observed by this instrument with a spectral resolution of ~1.6 Å. It is discussed in detail by Reeves, Huber, and Timothy (1977) and Reeves et al. (1977).

4. Results and Discussion

In Table I we summarise measurements of the ratios $R_1 = I(365.6 \text{ Å})/I(416.2 \text{ Å})$, $R_2 = I(482 \text{ Å})/I(416.2 \text{ Å})$, $R_3 = I(570 \text{ Å})/I(416.2 \text{ Å})$, $R_4 = I(416.8 \text{ Å})/I(416.2 \text{ Å})$, and $R_5 = I(359 \text{ Å})/I(416.2 \text{ Å})$ for an erupting prominence observed by Widing, Feldman, and Bhatia (1986) with the S082A spectrograph, as well as values of $R_2$, $R_3$, and $R_5$ for a flare and sunspot detected with the S-055 spectrometer by Doyle (1983) and Noyes et al. (1985), respectively. Also listed in the table are the theoretical ratios at the temperature of maximum NeV fractional abundance in ionisation equilibrium, $\log T_{\text{max}} = 5.5$ (Arnaud and Rothenflug, 1985). The observational data from the S082A instrument should be accurate to ± 30% (Keenan et al., 1986, 1988b), while the
Fig. 2. Theoretical Ne v emission line ratios plotted as a function of electron temperature at an electron density of $N_e = 10^{10}$ cm$^{-3}$, with: solid line: $R_2 = I(3P - 3P^0)/I(1D - 1D^0) = I(482 \ Å)/I(416.2 \ Å)$; dashed line: $R_3 = I(3P - 3D^0)/I(1D - 1D^0) = I(570 \ Å)/I(416.2 \ Å)$.

estimated uncertainty for the lower resolution S-055 spectra is $\pm 50\%$ for all line ratios (Noyes et al., 1985), apart from those containing the 482 Å transitions, for which it is approximately a factor of two (see below).

An inspection of Table I shows that, for the high resolution S082A observations, agreement between theory and experiment is generally good, with discrepancies of less

<table>
<thead>
<tr>
<th>Solar feature</th>
<th>$\lambda_1$ (Å)</th>
<th>$\lambda_2$ (Å)</th>
<th>$R$</th>
<th>Source</th>
<th>$R_{\text{theory}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Prominence</td>
<td>365.6</td>
<td>416.2</td>
<td>1.30</td>
<td>Widing et al. (1986)</td>
<td>0.52</td>
</tr>
<tr>
<td>Prominence</td>
<td>482</td>
<td>416.2</td>
<td>1.38</td>
<td>Widing et al. (1986)</td>
<td>1.36</td>
</tr>
<tr>
<td>Prominence</td>
<td>570</td>
<td>416.2</td>
<td>1.97</td>
<td>Widing et al. (1986)</td>
<td>1.60</td>
</tr>
<tr>
<td>Prominence</td>
<td>416.8</td>
<td>416.2</td>
<td>0.15</td>
<td>Widing et al. (1986)</td>
<td>0.12</td>
</tr>
<tr>
<td>Prominence</td>
<td>359</td>
<td>416.2</td>
<td>1.83</td>
<td>Widing et al. (1986)</td>
<td>1.10</td>
</tr>
<tr>
<td>Sept. 7, 1973 flare</td>
<td>482</td>
<td>416.2</td>
<td>1.14</td>
<td>Doyle (1983)</td>
<td>1.36</td>
</tr>
<tr>
<td>Sept. 7, 1973 flare</td>
<td>570</td>
<td>416.2</td>
<td>1.06</td>
<td>Doyle (1983)</td>
<td>1.60</td>
</tr>
<tr>
<td>Sunspot</td>
<td>482</td>
<td>416.2</td>
<td>0.53</td>
<td>Noyes et al. (1985)</td>
<td>1.36</td>
</tr>
<tr>
<td>Sunspot</td>
<td>570</td>
<td>416.2</td>
<td>0.95</td>
<td>Noyes et al. (1985)</td>
<td>1.60</td>
</tr>
<tr>
<td>Sunspot</td>
<td>359</td>
<td>416.2</td>
<td>1.40</td>
<td>Noyes et al. (1985)</td>
<td>1.10</td>
</tr>
</tbody>
</table>
than 20% for $R_2$, $R_3$, and $R_4$. However, the observed value of $R_1$ is approximately a factor of 2.5 larger than $R_{\text{theory}}$. Widing, Feldman, and Bhatia (1986) have noted that the intensity of the 365.6 Å transition is uncertain, and in addition it may be blended with Fe X (Dere, 1978), which will have the effect of increasing $R_1$.

The $R_5$ ratio in the prominence is also substantially larger than the value predicted from theory (by about a factor of 1.7), but in the lower resolution sunspot data the observed and theoretical results only differ by 20%, which is well within the observational errors (Noyes et al., 1985). However, in this sunspot the intensities of lines formed near $\log T_e = 5.5$ are up to 40 times brighter than the average quiet-Sun values of Vernazza and Reeves (1978), although lines formed near $\log T_e = 4.3$ and 6.0 are only enhanced by a factor of 2 (Doyle et al., 1985). Hence, any blending species in the 359 Å line probably contribute a smaller amount to the total flux in this case, especially if their temperatures of formation are significantly different from $\log T_e = 5.5$. Ions that may be responsible for the blend include Fe XI and Fe XIII (Dere, 1978), for which $\log T_{\text{max}} = 6.1$ and 6.2, respectively (Arnaud and Rothenflug, 1985).

For the other line ratios in the S-055 dataset ($R_2$ and $R_3$), agreement between theory and observation is not as good as is the case for the S082Å observations, especially in the sunspot, where $R_2$ is almost a factor of 3 smaller than $R_{\text{theory}}$. However, these results are probably to be expected due to the lower quality of the S-055 spectra. For example, Noyes et al. (1985) note that the uncertainty in the 482 Å line flux is approximately 80%.

Finally, we note that in the analysis of observational data, one is frequently faced with the problem of instrument calibration, a useful check on which is usually provided by the ratio of two lines emitted from a common upper level. The lines in the $R_1$ ratio ($^1D - ^1P^0$ at 365.6 Å; $^1D - ^1D^0$ at 416.2 Å) are not from a common upper level, but the ratio is density insensitive for $N_e > 10^9$ cm$^{-3}$ and an inspection of Figure 1 shows that it only varies by 14% between $\log T_e = 5.3$ and 6.0. Thus it should be a valuable calibration check for a high resolution extreme ultraviolet instrument in the spectral range 360–420 Å.

**Acknowledgements**

We would like to thank Prof. H. B. Gilbody for his continued interest in this work. FPK is grateful to the SERC for financial support.

**References**


