Ne vi LINE RATIOS IN THE SUN

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ABSTRACT

Recent calculations of electron impact excitation rates for Ne vi are used to derive theoretical electron density sensitive emission line ratios involving transitions in the wavelength range 399–563 Å. Electron densities deduced from the observed line ratios for solar flares, obtained with the Naval Research Laboratory's S082A slitless spectrograph on-board Skylab, are in excellent internal agreement and, furthermore, compare favorably with densities estimated from line ratios in O vi and Ne vii, which are formed at similar electron temperatures to Ne vi. These results provide experimental support for the accuracy of the atomic data adopted in the analysis.

Subject headings: atomic data — Sun: flares — Sun: UV radiation

1. INTRODUCTION

Emission lines arising from transitions in B-like ions are frequently observed in solar ultraviolet spectra (Vernazza & Reeves 1978; Sandlin et al. 1986; Feldman & Widing 1990). The potential usefulness of these lines to infer the electron temperature ($T_e$) and density ($N_e$) of the emitting plasma was first pointed out by Flower & Nussbaumer (1975a), who presented diagnostic line ratios for O iv which were derived using electron impact excitation rates calculated in the Distorted-Wave approximation (Eissner & Seaton 1972). Since then, many authors have calculated electron rates for B-like ions, and used these to derive theoretical line ratios applicable to solar spectra. Ions considered include C ii (Hayes & Nussbaumer 1984a, b; Lennon et al. 1985), N iii (Nussbaumer & Storey 1979; Kastner & Bhatia 1984a, b), O iv (Kastner & Bhatia 1984a), Si x (Flower & Nussbaumer 1975b; Saha & Treflitz 1982), S xii (Flower & Nussbaumer 1975b), Ar xiv, Ca xvi (Dere et al. 1979) and Fe xxii (Mason & Storey 1980).

Vernazza & Mason (1978) have employed several of the diagnostic calculations listed above to interpolate limited results for other B-like series members, including Ne vi. Recently however, Zhang, Graziani, & Pradhan (1993) and Zhang & Sampson (1993) have calculated electron rates for this ion, using the R-matrix method (Burke & Robb 1975) and the Relativistic Distorted-Wave approximation (Sampson et al. 1989; Zhang, Sampson, & Mohanty 1989). In this paper we use these atomic data to derive line intensity ratios for Ne vi, and compare them with solar flare observations from the S082A instrument on-board Skylab.

2. ATOMIC DATA

The model ion for Ne vi consisted of the eight energetically lowest LS states, i.e., 2s$^2$2p$^2$2P, 2s2p$^4$4P, 2s2p$^2$D, 2s$^2$S, 2p$^2$P, 2p$^4$4S, 2p$^2$P, and 2p$^4$P, making a total of 15 fine-structure levels. [Henceforth the 2s$^2$2p$^2$2P and 2p$^4$4P levels will be denoted $^2P_l$ (for lower) and $^2P_u$ (for upper), respectively, to avoid confusion]. Energies of all the ionic levels were obtained from Moore (1971).

Electron impact excitation rates for transitions among the 2s$^2$2p and 2s2p$^2$ levels of Ne vi were taken from Zhang et al. (1993), who calculated atomic data using the R-matrix code as adopted for the Opacity Project (Seaton 1987; Berrington et al. 1987). We note that these results are quite similar to the R-matrix calculations of Hayes (1992), who presented rate coefficients (in LS-coupling) for transitions from the $^2P_l$ and $^4P$ levels only. For transitions to and between the $^2P_l$ levels, we have adopted the electron rates of Zhang & Sampson (1993), which have been derived in the Relativistic Distorted-Wave approximation (Sampson et al. 1989; Zhang et al. 1989).

Einstein A-coefficients have been taken from Dankworth & Trefftz (1978), apart from the value for $^2P_{1/2}$-$^2P_{3/2}$, where we interpolated the calculations of Lennon et al. (1985), Nussbaumer & Storey (1982), and Flower & Nussbaumer (1975b) for C ii, O iv, and Na vii, respectively. As noted by, for example, Seaton (1964), excitation by protons will be important for the $^2P_{1/2}$-$^2P_{3/2}$ transition, and in the present analysis we have used the rates for C ii (Hayes & Nussbaumer 1984b), N iii (Nussbaumer & Storey 1979), and O iv (Flower & Nussbaumer 1975a) to extrapolate results for Ne vi, using procedures discussed by Keenan (1988).

3. OBSERVATIONAL DATA

Ne vi emission lines were observed in the solar spectrum by the Naval Research Laboratory's XUV slitless spectrograph (S082A) on-board Skylab (Feldman & Widing 1990). This instrument covered the wavelength range 171–630 Å, with a maximum spectral resolution of ~0.1 Å and a spatial resolution of 2". It is discussed in detail by Tousey et al. (1977) and Dere (1978). The following Ne vi transitions were identi-
fied: $^{2}P_{1/2} - ^{2}P_{3/2} (399.83 \text{ Å}), ^{2}P_{1/2} - ^{2}P_{1/2} (401.14 \text{ Å}), ^{2}P_{3/2} - ^{2}P_{3/2} (401.94 \text{ Å}), ^{2}P_{1/2} - ^{2}P_{1/2} (433.17 \text{ Å}), ^{2}P_{1/2} - ^{2}P_{3/2} (435.65 \text{ Å}), ^{2}P_{3/2} - ^{2}P_{1/2} (452.74 \text{ Å}), ^{2}P_{5/2} - ^{2}D_{3/2} (454.07 \text{ Å}), ^{2}P_{1/2} - ^{2}D_{3/2} (558.60 \text{ Å}),$ and $^{2}P_{3/2} - ^{2}D_{3/2} (562.79 \text{ Å}).$ We note that the $^{2}P_{1/2} - ^{2}P_{1/2}$ transition at 403.28 Å was also detected, but it is blended with Mg vi (Widing, Feldman, & Bhatia 1986).

Vernazza & Mason (1978) have pointed out that emission line ratios involving the above transitions should be useful as electron density diagnostics for solar flares, as the $^{4}P$ levels reach Boltzmann equilibrium for values of $N_e \geq 10^{11} \text{ cm}^{-3}.$ In Table 1 we therefore summarize measurements of the line ratios,

$$R_1 = I(^{4}P_{5/2} - ^{4}S)/I(^{2}P_{3/2} - ^{2}D_{3/2}) = I(454.07 \text{ Å})/I(562.79 \text{ Å}),$$

$$R_2 = I(^{4}P_{5/2} - ^{4}S)/I(^{2}P_{1/2} - ^{2}P_{1/2}) = I(454.07 \text{ Å})/I(435.65 \text{ Å}),$$

$$R_3 = I(^{4}P_{5/2} - ^{4}S)/I(^{2}P_{1/2} - ^{2}D_{3/2}) = I(454.07 \text{ Å})/I(558.60 \text{ Å}),$$

$$R_4 = I(^{4}P_{5/2} - ^{4}S)/I(^{2}P_{1/2} - ^{2}P_{1/2}) = I(454.07 \text{ Å})/I(401.14 \text{ Å}),$$

$$R_5 = I(^{4}P_{5/2} - ^{4}S)/I(^{2}P_{3/2} - ^{2}P_{3/2}) = I(454.07 \text{ Å})/I(401.94 \text{ Å}),$$

$$R_6 = I(^{4}P_{5/2} - ^{4}S)/I(^{2}P_{3/2} - ^{2}P_{1/2}) = I(454.07 \text{ Å})/I(433.17 \text{ Å}),$$

$$R_7 = I(^{4}P_{5/2} - ^{4}S)/I(^{2}P_{1/2} - ^{2}P_{3/2}) = I(454.07 \text{ Å})/I(399.83 \text{ Å}),$$

and

$$R_8 = I(^{4}P_{3/2} - ^{4}S)/I(^{2}P_{3/2} - ^{2}S) = I(452.74 \text{ Å})/I(435.65 \text{ Å}).$$

for the solar flares of 1973 August 9 at 1555 UT (discussed in detail by Dere & Cook 1979; Dere et al. 1979), 1973 December 2 at 1518 UT (Feldman & Widing 1990), and 1973 December 17 at 0048 UT (Widing & Spicer 1980; Widing & Cook 1987). These data should be accurate to approximately ±30% (Keenan et al. 1984; Widing et al. 1986), except as noted below.

With respect to the observed Ne vi intensities, we note that the density sensitive 454.07 Å line is well observed in the 1973 December 2 flare, is weaker but useful in the 1973 August 9 flare but is only marginal in the 1973 December 17 event, where it is placed on the toe of the HD calibration curve. The intensity of the weaker 452.74 Å component also could not be read in this flare. For this reason, the values of log $N_e$ derived for the December 17 event may set only an upper limit on the electron density.

4. RESULTS AND DISCUSSION

Using the atomic data discussed in § 3 in conjunction with the statistical equilibrium code of Dufton (1977), the $R_1$-$R_8$ emission line ratios were derived for a range of electron temperatures and densities. The following assumptions were made in the calculations: (i) that photoexcitation and de-excitation rates are negligible in comparison with the corresponding collisional rates; (ii) that ionization to and recombination from other ionic levels is slow compared with bound-bound rates; (iii) that all transitions are optically thin. Further details of the procedures involved may be found in Dufton (1977).

In Figure 1 we plot the $R_1$-$R_8$ ratios as a function of log $N_e$ at the electron temperature of maximum Ne vi fractional abundance in ionization equilibrium, $T_e = T_{max} = 4.5 \times 10^5$ K (Arnaud & Rothenflug 1985), although the results are relatively insensitive to the adopted value of $T_e.$ For example, changing the electron temperature from 4.5 to 4.0 $\times 10^5$ K leads to a variation in the theoretical ratios of ≤5% at $N_e = 10^9 \text{ cm}^{-3}$, which decreases to ≤2% at $N_e = 10^{10} \text{ cm}^{-3}$. This is in sharp contrast to the results of Vernazza & Mason (1978), who found a factor of ~2 variation in $R_1$ for a similar change in $T_e.$ The large temperature sensitivity for $R_1$ derived by Vernazza & Mason is difficult to understand, as the electron excitation rates of the relevant transitions are not strongly dependent on $T_e$ (Zhang et al. 1993; Zhang & Sampson 1993), and in addition

<table>
<thead>
<tr>
<th>Solar Feature</th>
<th>$R_1$</th>
<th>$R_2$</th>
<th>$R_3$</th>
<th>$R_4$</th>
<th>$R_5$</th>
<th>$R_6$</th>
<th>$R_7$</th>
<th>$R_8$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1973 Aug 9 flare, 1555 UT</td>
<td>0.085</td>
<td>0.264</td>
<td>0.091</td>
<td>0.123</td>
<td>0.104</td>
<td>0.461</td>
<td>0.233</td>
<td>0.177</td>
</tr>
<tr>
<td>1973 Dec 2 flare, 1518 UT</td>
<td>0.104</td>
<td>0.287</td>
<td>0.198</td>
<td>0.152</td>
<td>0.062</td>
<td>0.478</td>
<td>0.224</td>
<td>0.174</td>
</tr>
<tr>
<td>1973 Dec 17 flare, 0048 UT</td>
<td>0.054</td>
<td>0.151</td>
<td>0.106</td>
<td>0.061</td>
<td>0.193</td>
<td>0.137</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
the energy separation of the upper levels of the transitions \( E_U - E_L \) is only \( \approx 2 \times 10^3 \) K, so that at temperatures near \( 4 \times 10^5 \) K one would not expect the ratio to be \( T_e \)-sensitive (see, for example, Keenan 1992). The theoretical values of \( R_1 - R_8 \) in Figure 1 should be accurate to approximately \( \pm 15\% \).

We note that the ratios \( R_6 \), \( R_7 \), and \( R_8 \) have the same density dependence as \( R_2 \), \( R_3 \), and \( R_4 \), respectively, except that

\[
R_6 = 1.67 R_2 ,
\]

\[
R_7 = 5.09 R_3 ,
\]

and

\[
R_8 = 0.67 R_2 .
\]

The logarithmic electron densities deduced from the observed values of \( R_1 - R_8 \) are summarized in Table 2, along with the average of these (log \( N_e \)). In view of the observational uncertainties in the line ratios (see § 3), the derived values of log \( N_e \) should be accurate to approximately \( \pm 0.3 \) dex. Also given in the table are the densities estimated from emission line ratios in O V or Ne v \( (\text{which are formed at electron temperatures close to that of Ne vi, } T_{\text{max}}(\text{O V}) \approx 3 \times 10^5 \text{ K}; T_{\text{max}}(\text{Ne v}) \approx 5 \times 10^5 \text{ K}) \) by Arnaud & Rothenflug (1985), where we have used observational data from the references in § 3 to individual flares, and the diagnostic calculations of Keenan et al. (1991) and Keenan, McCann & Widing (1990) for O V and Ne v, respectively.

An inspection of Table 2 reveals that electron densities determined from \( R_1 - R_8 \) are generally in very good agreement.

<table>
<thead>
<tr>
<th>Solar Feature</th>
<th>( R_1 )</th>
<th>( R_2 )</th>
<th>( R_3 )</th>
<th>( R_4 )</th>
<th>( R_5 )</th>
<th>( R_6 )</th>
<th>( R_7 )</th>
<th>( R_8 )</th>
<th>( \log N_e )</th>
<th>( \log N_e(\text{O V, Ne vi}) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1973 Aug 9 flare, 1555 UT</td>
<td>12.1</td>
<td>12.2</td>
<td>11.9</td>
<td>11.9</td>
<td>12.5</td>
<td>12.3</td>
<td>12.0</td>
<td>12.3</td>
<td>12.1</td>
<td>11.8</td>
</tr>
<tr>
<td>1973 Dec 2 flare, 1518 UT</td>
<td>12.3</td>
<td>12.3</td>
<td>12.3</td>
<td>12.2</td>
<td>12.3</td>
<td>12.3</td>
<td>12.0</td>
<td>12.3</td>
<td>12.3</td>
<td>12.3</td>
</tr>
<tr>
<td>1973 Dec 17 flare, 0048 UT</td>
<td>11.8</td>
<td>11.8</td>
<td>11.9</td>
<td>11.6</td>
<td>12.3</td>
<td>11.7</td>
<td>11.7</td>
<td>11.7</td>
<td>11.8</td>
<td>11.6</td>
</tr>
</tbody>
</table>

This is illustrated by the fact that they differ by typically \( \sim 0.1 \) dex with log \( N_e \), and the discrepancy only exceeds 0.3 dex in two instances, namely those of \( R_5 \) in the 1973 August 9 and December 17 flares. However in these cases, relatively small changes in the observed line ratios \( (\lesssim 28\%) \) would bring the derived electron densities into agreement with those derived from other ratios; such a change is compatible with the observational errors in the data (see § 3).

Finally, we can see from Table 2 that the average Ne vi electron densities compare favorably with those deduced from line ratios in species formed at similar electron temperatures (O V or Ne vi), with discrepancies of typically 0.2 dex. These results provide observational support for the accuracy of the Ne vi atomic data adopted in the present analysis, and indicate that the diagnostics may be used to derive reliable values of \( N_e \) in high density solar features, such as flares. The present analysis also implies that the Ne vi atomic data may be employed in the derivation of accurate neon abundances in the solar transition region (Feldman 1992; Widing & Feldman 1992).

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REFERENCES

Arnaud, M., & Rothenflug, R. 1985, A\&AS, 60, 425


Dankworth, W. & Trefitz, E. 1973, A\&A, 68, 164


Flower, D. R., & Nussbaumer, H. 1975a, A\&A, 45, 145


Keenan, F. P. 1988, Phys. Scripta, 37, 57


Moore, C. E. 1971, Atomic Energy Levels, NSRDS-NBS 35

Nussbaumer, H., & Storey, P. J. 1979, A\&A, 71, L5

---. 1982, A\&A, 115, 205


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