Skylab Observations of Temperature and Density Sensitive Emission Line Ratios in Ne VI

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Recent calculations of electron and proton impact excitation rates in Ne VI are used to derive the intensity ratios of lines in the ~402–1006 Å wavelength range as a function of electron temperature (T_e) and density (N_e). These results are presented in the form of ratio–ratio diagrams, which should in principle allow both N_e and T_e to be deduced for the Ne VI line emitting region of a plasma. Electron temperatures and densities derived from ratio–ratio diagrams involving the 562.7, 997.4, 999.6 and 1006.1 Å lines, in conjunction with observational data for a sunspot obtained with the Harvard S-0555 spectrometer on board *Skylab*, are found to be compatible, and in good agreement with plasma parameters determined using other methods. This provides some support for the diagnostic calculations presented in this paper, and hence the atomic data used in their derivation. However agreement between theory and observation is very poor for other Ne VI lines in the sunspot spectrum, and for most transitions observed in S-0555 active region and flare data, which is probably due to blending with lines from N III, Mg VI and Mg VII. The application of the calculations to non-solar EUV sources is discussed.

1. Introduction

Emission lines arising from $2s^22p$–$2s2p^2$ transitions in boron-like ions have often been identified in solar UV and EUV spectra. Flower & Nussbaumer (1975), first noted the diagnostic potential of these lines presenting electron density and temperature sensitive emission line ratios for O IV calculated using electron impact excitation rates derived in the Distorted-Wave approximation (Eissner & Seaton 1972). Zhang, Graziani & Pradhan (1994) have calculated electron excitation rates for Ne VI using the R-matrix method of Burke & Robb (1975) and these results are used here to derive solar plasma diagnostics for this ion. An assessment of the validity of these diagnostics is made by way of a comparison with observations from the S-0555 instrument on board *Skylab*.

2. Atomic Data and Theoretical Line Ratios

The Ne VI model ion is discussed in detail by Keenan et al. (1995) where details of the ratio calculations may be found. The line ratios considered by us in the present paper include the following:

S. Bowyer and R. F. Malina (eds.), Astrophysics in the Extreme Ultraviolet, 537–541.

$$\mathrm{R}_1 = \mathrm{I}(2s^2 2p\ ^2\mathrm{P}_{3/2}\text{–}2s2p^2\ ^4\mathrm{P}_{3/2})/\mathrm{I}(2s^2 2p\ ^2\mathrm{P}_{1/2}\text{–}2s2p^2\ ^4\mathrm{P}_{1/2}) = \mathrm{I}(1006.1\ \text{Å})/\mathrm{I}(997.4\ \text{Å}),$$

$$\mathrm{R}_2 = \mathrm{I}(2s^2 2p\ ^2\mathrm{P}_{3/2}\text{–}2s2p^2\ ^4\mathrm{P}_{5/2})/\mathrm{I}(2s^2 2p\ ^2\mathrm{P}_{1/2}\text{–}2s2p^2\ ^4\mathrm{P}_{1/2}) = \mathrm{I}(999.6\ \text{Å})/\mathrm{I}(997.4\ \text{Å}),$$

$$\mathrm{R}_3 = \mathrm{I}(2s^2 2p\ ^2\mathrm{P}_{3/2}\text{–}2s2p^2\ ^4\mathrm{P}_{3/2})/\mathrm{I}(2s^2 2p\ ^2\mathrm{P}_{3/2}\text{–}2s2p^2\ ^2\mathrm{D}_{3/2,5/2}) = \mathrm{I}(1006.1\ \text{Å})/\mathrm{I}(562.7\ \text{Å}),$$

$$\mathrm{R}_4 = \mathrm{I}(2s^2 2p\ ^2\mathrm{P}_{3/2}\text{–}2s2p^2\ ^2\mathrm{S})/\mathrm{I}(2s^2 2p\ ^2\mathrm{P}_{3/2}\text{–}2s2p^2\ ^2\mathrm{D}_{3/2,5/2}) = \mathrm{I}(435.7\ \text{Å})/\mathrm{I}(562.7\ \text{Å}),$$

$$\mathrm{R}_5 = \mathrm{I}(2s^2 2p\ ^2\mathrm{P}_{1/2}\text{–}2s2p^2\ ^2\mathrm{S})/\mathrm{I}(2s^2 2p\ ^2\mathrm{P}_{3/2}\text{–}2s2p^2\ ^2\mathrm{D}_{3/2,5/2}) = \mathrm{I}(433.2\ \text{Å})/\mathrm{I}(562.7\ \text{Å}),$$

$$\mathrm{R}_6 = \mathrm{I}(2s^2 2p\ ^2\mathrm{P}_{3/2}\text{–}2s2p^2\ ^2\mathrm{P}_{1/2})/\mathrm{I}(2s^2 2p\ ^2\mathrm{P}_{3/2}\text{–}2s2p^2\ ^2\mathrm{D}_{3/2,5/2}) = \mathrm{I}(403.3\ \text{Å})/\mathrm{I}(562.7\ \text{Å}),$$

and

$$\mathrm{R}_7 = \mathrm{I}[(2s^2 2p\ ^2\mathrm{P}_{1/2}\ \text{–}2s2p^2\ ^2\mathrm{P}_{1/2}) + (2s^2 2p\ ^2\mathrm{P}_{3/2}\text{–}2s2p^2\ ^2\mathrm{P}_{3/2})]/\mathrm{I}(2s^2 2p\ ^2\mathrm{P}_{3/2}\text{–}\ 2s2p^2\ ^2\mathrm{D}_{3/2,5/2}) = \mathrm{I}(401.9\ \text{Å})/\mathrm{I}(562.7\ \text{Å}).$$

Under solar conditions, the above ratios are usually sensitive to variations in both the electron temperature and density. Hence in principle they should only be used to determine N_e or T_e when the other plasma parameter has been independently estimated. For example, Figure 1 is the ratio–ratio diagram of R_1 *vs* R_3 for a grid of ($\log \mathrm{N}_e$, $\log \mathrm{T}_e$) values. Using such figures it is possible to simultaneously determine both the electron temperature and density from the measured values of the ratios.

3. Observational Data

The Ne VI lines in the wavelength interval 401.9–1006.1 Å discussed in § 2 have been identified in solar spectra obtained with the Harvard S-0555 EUV spectrometer on board *Skylab*. This instrument, which covered the wavelength region 280–1350 Å, observed a spatial area of 5 × 5 arcsec with a spectral resolution of ~1.5 Å (FWHM) using an integration time of 0.04 s and a step length of 0.2112 Å. It is discussed in detail by Reeves, Huber & Timothy (1977) and Reeves et al. (1977). We have determined Ne VI line strengths, and hence ratios, by using the STARLINK reduction package DIPSO (Howarth & Murray 1991) to fit Gaussian profiles to the S-0555 spectra; such profiles were found to give acceptable fits to the observational data. Line intensities derived from the profile fitting should be accurate to typically ±20%, implying that the resultant line ratios have an uncertainty of ±30%. The derived values of R_1 to R_7 are summarised in Table 1 for a sunspot located close to disk centre recorded on August 29, 1973 (discussed by Doyle et al. 1985), an active region observed at the limb on December 16, 1973 (Doyle, Mason & Vernazza 1985), and a large two-ribbon flare observed on September 7, 1973 at 12:55, 14:03 and 15:52 UT (Doyle 1983).

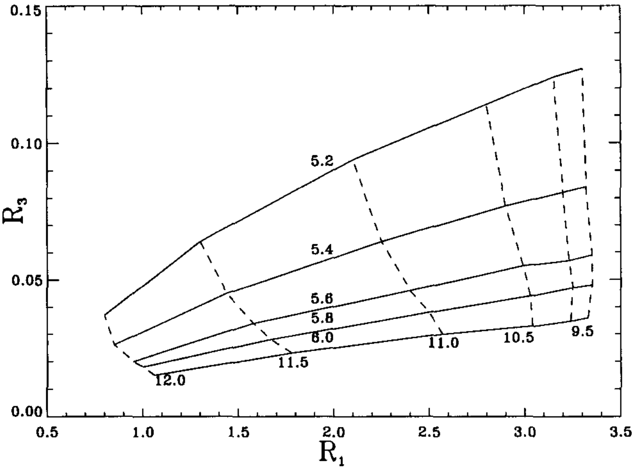

FIGURE 1. Plot of the theoretical Ne VI emission line ratio $R_1 = I(2s^22p\ ^2P_{3/2}\text{–}2s2p^2\ ^4P_{3/2})/I(2s^22p\ ^2P_{1/2}\text{–}2s2p^2\ ^4P_{1/2}) = I(1006.1\ \text{Å})/I(997.4\ \text{Å})$ against $R_3 = I(2s^22p\ ^2P_{3/2}\text{–}2s2p^2\ ^4P_{3/2})/I(2s^22p\ ^2P_{3/2}\text{–}2s2p^2\ ^2D_{3/2,5/2}) = I(1006.1\ \text{Å})/I(562.7\ \text{Å})$, where I is in energy units, for a range of logarithmic electron temperatures (log T_e = 5.2–6.0; T_e in K) and logarithmic electron densities (log N_e = 9.5– 12.0; N_e in cm^{-3}). Points of constant T_e are connected by solid lines, while those of constant N_e are joined by dashed lines. Note that the curves for log $N_e < 9.5$ are coincident with that for log N_e = 9.5.

4. Results and Discussion

In Table 2 we summarise the logarithmic electron densities and temperatures derived from the observed values of R_1 to R_7 in conjunction with the diagnostic calculations. For the sunspot, the plasma parameters estimated from (R_1, R_3) and (R_2, R_3) are consistent, with discrepancies of ~0.1 dex in both log N_e and log T_e. These differences correspond to only a ~10% change in the line ratios, which is well within both the theoretical (±20%) and observational (±30%) uncertainties. However the ratios R_4 to R_7 in the sunspot, R_3 to R_6 in the active region and R_3 to R_7 in the flare, are all much larger than the theoretical low temperature limits. Such discrepancies are too great to be ascribed to theoretical or observational errors. In some of these instances, we have at least been able to estimate a log N_e range from the R_1 ratio portions of the diagnostic curves, by assuming that the temperatures of the Ne VI emitting regions lie within the range plotted (log T_e = 5.2–6.0), where the fractional abundance of Ne VI in ionisation equilibrium is $\geq 10^{-3}$ (Arnaud & Rothenflug 1985). The general disagreement between theory and observation for the R_3 to R_7 ratios is most likely due to blending. However for the flare data there may be additional problems, as typically ~100 seconds were needed by the S-0555 instrument to scan through the spectrum from the long wavelength lines at ~1000 Å to the transitions between ~400–563 Å, during which time there may have been significant variations in the intensities of the flare lines, which would hence affect any determinations of R_3. We note that in the few instances where we have been able to measure reliable Ne VI line ratios, and hence determine plasma parameters, these are in good agreement with other independent estimates. For example, Keenan et al. (1994) derived log N_e = 11.1 and 10.4 for the flare at 14:03 and 15:52 UT, respectively, using line ratios in O V, which is formed at a similar electron temperature to Ne VI (log T_{max}(O V)

TABLE 1. Observed Ne VI emission line ratios

Solar feature	R_1	R_2	R_3	R_4	R_5	R_6	R_7
(a) Sunspot	2.85	5.31	5.64×10^{-2}	1.06	1.17	1.86	4.21
(b) Active Region	...	...	2.01×10^{-1}	4.60	2.82	1.98	1.71
(c) Flare, 12:55 UT	2.43	...	5.73×10^{-1}	...	1.01	...	4.37
(d) Flare, 14:03 UT	1.83	...	1.07	...	1.89	...	7.34
(e) Flare, 15:52 UT	3.25	...	4.69×10^{-1}	...	1.92	...	5.53

TABLE 2. Ne VI logarithmic electron densities and temperatures (log N_e, log T_e) derived from ratio–ratio diagrams (L = observed line ratio is larger than the theoretical low temperature limit)

Feature	(R_1,R_3)	(R_2,R_3)	(R_1,R_4)	(R_1,R_5)	(R_1,R_6)	(R_1,R_7)
(a) SS	10.6,5.60	10.7,5.52	...,L	...,L	...,L	...,L
(b) AR	...,L	...,L	...,L	...,L	...,L	...,5.51
(c) Flare	10.8–11.1,L	...,L	......	10.8–11.1,L	......	10.8–11.1,L
(d) Flare	11.2–11.4,L	...,L	......	11.2,11.4,L	......	11.2–11.4,L
(e) Flare	9.6–10.0,L	...,L	......	9.6–10.0,L	......	9.6-10.0,L

= 5.40; Arnaud & Rothenflug 1985). These densities are compatible with those listed in Table 2. Hence there is limited observational support for the accuracy of the theoretical diagnostics presented in this paper, and hence the atomic data used in their derivation.

Clearly, higher spectral resolution observations of the Ne VI lines in the 400–1000 Å wavelength range are required, in order to remove the problems of blending, and hence reliably determine emission line ratios which may be used to determine both the electron temperature and density of the Ne VI emitting region of the solar atmosphere. Such observations should be possible in the future using the *Coronal Diagnostic Spectrometer* (*CDS*) and *Solar Ultraviolet Measurements of Emitted Radiation* (*SUMER*) instruments on the upcoming *Solar and Heliospheric Observatory* (*SOHO*) mission, due for launch in 1995. CDS covers the 150–800 Å wavelength range which will allow measurements of the R_4 to R_7 ratios in Ne VI, while SUMER will obtain spectra between 500–1600 Å permitting determinations of R_1 to R_3. However for other astronomical sources the situation is more problematical. Although the *Extreme Ultraviolet Explorer* (*EUVE*) satellite observes the 280–760 Å wavelength region in the LW passband (Bowyer & Malina 1991), which contains the Ne VI 401.9–562.7 Å transitions, these data are only obtained at a resolution of ~ 2 Å. As a result, the only Ne VI line that has been reliably observed to the best of our knowledge, is 401.9 Å (Drake, Laming & Widing 1995). However, the *Lyman/FUSE* mission planned for the end of the decade will obtain spectra in the 912–1500 Å region at a resolution of ~ 0.04 Å (Linsky 1993). This should be sufficient to accurately determine values of the R_1 and R_2 ratios in Ne VI, and hence investigate their usefulness as plasma diagnostics for astronomical sources.

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