EUV PLASMA DIAGNOSTICS FOR NITROGEN-LIKE IONS FROM SPECTRA OBTAINED BY SUMER/SOHO

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ABSTRACT

We discuss the potential for plasma diagnostics of forbidden transitions from the ground levels in the nitrogen-like ions: Al VII, Si VIII, P IX, S X, Ar XII, K XIII and Ca XIV. These transitions fall in the UV spectral range and have been recently observed by the SOHO/SUMER instrument in the solar spectrum. Some of the lines used in the present study have been measured by SUMER for the first time: higher resolution and sensitivity allow for the identification and measurement of weaker lines than previously, at positions higher off the solar limb. We show that current atomic data are still not able to reproduce the observations and that further work is required to solve inconsistencies between observations and theoretical predictions.

Key words: Sun; plasma diagnostics; atomic data.

1. INTRODUCTION

Emission lines arising from transitions in ions of the nitrogen isoelectronic sequence are frequently observed in the spectra of astrophysical sources, including the solar transition region and corona. The inference of electron density in the gaseous nebulae using the line intensity ratio of forbidden lines that arise from transitions within the ground configuration of O II (2s²2p⁵) is well known [1]. The density sensitivity occurs for the same transitions in other ions within the N I isoelectronic sequence and is useful in the UV for solar application for Mg VI, Si VIII, S X, and Ar XII [2,3,4,5]. Allowed lines from these ions have also been shown to be good density monitors of the emitting regions [3,6].

The SUMER (Solar Ultraviolet measurements of Emitted Radiation) spectograph on the SOHO spacecraft is offering an unprecedented view of the solar spectrum in the wavelength range 465-1610 Å [7,8]. In observations on the solar disk, cool chromospheric and low transition region lines dominate the spectrum, while in off-disk observations coronal lines become most prominent in this wavelength region. In this paper we revisit the density-dependence of the nitrogen-like ions Al VII, Si VIII, P IX, S X, Ar XII, K XIII and Ca XIV: the forbidden transitions within the levels in their ground configurations fall within the SUMER bandpass.

As shown in Fig. 1 the logarithmic temperatures of formation for these ions are 5.8, 6.0, 6.0, 6.2, 6.4, 6.4 and 6.5 respectively [9], and thus these lines can be used for plasma diagnostics of both quiet and active solar corona. Some of the lines used in the present study are measured for the first time (Al VII 1056.77 Å, both the P IX line pairs): higher resolution and sensitivity of the SUMER spectograph allow for the identification and measurement of weaker lines than previously, at positions higher off the solar limb. Most of these lines were not previously observed for two related reasons: (1) insufficient instrumental sensitivity, which led to (2) inability to observe sufficiently low density regions where these line ratios have their full diagnostic properties.

The availability of such a complete dataset for the forbidden N-like lines allows for the first time to make a systematic assessment of the density diagnostic potential along the N-like sequence. Use is made of the Version 4.0 of the CHIANTI database [10,11] to calculate theoretical line ratios; the present work also allows to make a complete assessment of the quality of the CHIANTI atomic data that are necessary to evaluate theoretical line emissivities for the considered lines.

2. ATOMIC DATA AND OBSERVATIONS

In order to better check the accuracy of CHIANTI line emissivities of N-like ions, it is best to compare theoretical and experimental line ratios obtained in

Proc. 'SOLMAG: Magnetic Coupling of the Solar Atmosphere Euroconference and IAU Colloquium 188'
Santorini, Greece, 11-15 June 2002 (ESA SP-505, October 2002)

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spectra emitted by a source as isothermal as possible. Since we take into account lines from ions formed at temperatures ranging from $6 \times 10^5$ K to $3.2 \times 10^6$ K, typical of quiet Sun and active regions, we have considered two distinct datasets. Observed line intensities for lines from Al VII to S X are taken from the comprehensive SUMER spectral atlas for quiet Sun, off-disk corona [12]: the emitting plasma considered in [12] was shown to be isothermal. Observations for ions from Ar XII to Ca XIV are taken from a hot active region spectrum [13]: the plasma was highly structured and presented several different loop structures along the line of sight.

The atomic data in the CHIANTI database, version 4 have been used to calculate the line emissivity ratios which are shown in Figs. 2 and 3. In Version 4, CHIANTI data for the N-like sequence have been entirely renewed, by substituting the older [3] Distorted Wave (DW) calculations with DW calculations from [14]. The latter provide atomic data and DW transition probabilities for the first 15 fine structure levels only. Moreover, a R-Matrix data have been used for the forbidden transitions within the ground configuration of Si VIII ([15]) and S X ([16]). Si VIII and Ar XII levels include additional data for other 57 energy levels taken from other DW calculations ([4] and [17]) respectively. The effect of resonances in R-Matrix transition probabilities, and of radiative cascades from higher excitation levels may influence level populations of the ground configuration levels and alter intensity ratios from the ground forbidden transitions considered in the present work.

Measured line intensities, intensity ratios and inferred electron densities are listed in Table 1. New calculations of atomic data for Si VIII ion are now available ([4]), which allows the analysis of all allowed $n = 3 \rightarrow n = 3$ transitions visible in the SUMER wavelength range. Preliminary analysis of spectra of such transitions has shown their potential for plasma diagnostics ([4]): a more detailed analysis of observations of $n = 3 \rightarrow n = 3$ Si VIII lines is beyond the scope of the present work and will be discussed elsewhere ([18]).

3. RESULTS AND DISCUSSION

Figure 2 demonstrates that the $(^4S_{3/2} - ^2P_{3/2})/(^4S_{3/2} - ^2P_{1/2})$ line intensity ratio can be effectively used as tool for density diagnostics in the solar corona in quiet and active region, as ratios of ions from Mg VI to Si VIII are density sensitive in the density range typical of the solar corona. With the only exception of Mg VI, these line ratios are suggested for density diagnostics for the first time. Heavier elements (P IX, S X and Ar XII) on the contrary present nearly constant ratios up to $10^{10}$ cm$^{-3}$, and are density sensitive at higher densities.

The $(^4S_{3/2} - ^2D_{5/2})/(^4S_{3/2} - ^2D_{5/2})$ ratio constitutes an even more useful tool for density diagnostics, as its density sensitivity is much more marked. Ratios

![Figure 1. Ion fractions of N-like ions as a function of Log T, from [9].](image1)

![Figure 2. Line intensity ratio involving the ground-forbidden transitions $(^4S_{3/2} - ^2D_{3/2})/(^4S_{3/2} - ^2D_{5/2})$ as a function of the electron density, along the N-like sequence.](image2)

![Figure 3. Line intensity ratio involving the ground-forbidden transitions $(^4S_{3/2} - ^2D_{3/2})/(^4S_{3/2} - ^2D_{5/2})$ as a function of the electron density, along the N-like sequence.](image3)
Table 1. Observed intensities and intensity ratios analyzed in the present work. Data are from off-disk observations of quiet Sun (Al VII to S X) and of a strong active region (Ar XII to Ca XIV).

<table>
<thead>
<tr>
<th>Ion</th>
<th>( \log T_M )</th>
<th>Wvl. (( \text{Å} ))</th>
<th>Transition</th>
<th>( I_{\text{obs}} )</th>
<th>Ratio</th>
<th>( \log N_e )</th>
<th>Solar region</th>
</tr>
</thead>
<tbody>
<tr>
<td>Al VII</td>
<td>5.8</td>
<td>1053.84</td>
<td>(^4S_{3/2} \rightarrow ^2P_{3/2})</td>
<td>0.40±0.02</td>
<td>2.86±0.6</td>
<td>≤ 9.9</td>
<td>Quiet Sun</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1056.77</td>
<td>(^4S_{3/2} \rightarrow ^2P_{1/2})</td>
<td>0.14±0.01</td>
<td>1.0</td>
<td>Quiet Sun</td>
<td></td>
</tr>
<tr>
<td>Si VIII</td>
<td>6.0</td>
<td>944.38</td>
<td>(^4S_{3/2} \rightarrow ^2P_{3/2})</td>
<td>22.0±0.4</td>
<td>2.89±0.05</td>
<td>9.7±0.1</td>
<td>Quiet Sun</td>
</tr>
<tr>
<td></td>
<td></td>
<td>949.22</td>
<td>(^4S_{3/2} \rightarrow ^2P_{1/2})</td>
<td>7.6±0.04</td>
<td>1.0</td>
<td>Quiet Sun</td>
<td></td>
</tr>
<tr>
<td>P IX</td>
<td>6.0</td>
<td>853.54</td>
<td>(^4S_{3/2} \rightarrow ^2P_{3/2})</td>
<td>0.31±0.02</td>
<td>3.37±0.36</td>
<td>8.1±0.1</td>
<td>Quiet Sun</td>
</tr>
<tr>
<td></td>
<td></td>
<td>861.10</td>
<td>(^4S_{3/2} \rightarrow ^2P_{1/2})</td>
<td>0.09±0.01</td>
<td>1.0</td>
<td>Quiet Sun</td>
<td></td>
</tr>
<tr>
<td>S X</td>
<td>6.2</td>
<td>776.37</td>
<td>(^4S_{3/2} \rightarrow ^2P_{3/2})</td>
<td>9.7±0.2</td>
<td>2.0±0.1</td>
<td>7.0±0.25</td>
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<tr>
<td></td>
<td></td>
<td>787.43</td>
<td>(^4S_{3/2} \rightarrow ^2P_{1/2})</td>
<td>4.8±0.1</td>
<td>1.0</td>
<td>Quiet Sun</td>
<td></td>
</tr>
<tr>
<td>Ar XII</td>
<td>6.4</td>
<td>649.14</td>
<td>(^4S_{3/2} \rightarrow ^2P_{3/2})</td>
<td>2.7±0.2</td>
<td>6.1±0.8</td>
<td>Exp. High</td>
<td>Active region</td>
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<tr>
<td></td>
<td></td>
<td>670.35</td>
<td>(^4S_{3/2} \rightarrow ^2P_{1/2})</td>
<td>0.44±0.05</td>
<td>1.0</td>
<td>Active region</td>
<td></td>
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<tr>
<td>Si VIII</td>
<td>6.0</td>
<td>1440.49</td>
<td>(^4S_{3/2} \rightarrow ^2D_{5/2})</td>
<td>4.1±0.1</td>
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<td></td>
<td>1445.75</td>
<td>(^4S_{3/2} \rightarrow ^2D_{3/2})</td>
<td>50.4±0.6</td>
<td>12.3±0.3</td>
<td>8.12±0.1</td>
<td>Quiet Sun</td>
</tr>
<tr>
<td>P IX</td>
<td>6.0</td>
<td>1307.57</td>
<td>(^4S_{3/2} \rightarrow ^2D_{5/2})</td>
<td>0.12±0.01</td>
<td>1.0</td>
<td>Quiet Sun</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>1317.65</td>
<td>(^4S_{3/2} \rightarrow ^2D_{3/2})</td>
<td>1.35±0.04</td>
<td>11.3±1.0</td>
<td>8.95±0.1</td>
<td>Quiet Sun</td>
</tr>
<tr>
<td>S X</td>
<td>6.2</td>
<td>1196.20</td>
<td>(^4S_{3/2} \rightarrow ^2D_{5/2})</td>
<td>18.4±0.2</td>
<td>1.0</td>
<td>Quiet Sun</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>1212.93</td>
<td>(^4S_{3/2} \rightarrow ^2D_{3/2})</td>
<td>42.4±0.4</td>
<td>2.3±0.03</td>
<td>8.10±0.1</td>
<td>Quiet Sun</td>
</tr>
<tr>
<td>Ar XII</td>
<td>6.4</td>
<td>1018.89</td>
<td>(^4S_{3/2} \rightarrow ^2D_{5/2})</td>
<td>3.6±0.14</td>
<td>1.0</td>
<td>9.60±0.2</td>
<td>Active region</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1054.57</td>
<td>(^4S_{3/2} \rightarrow ^2D_{3/2})</td>
<td>10.8±0.2</td>
<td>3.0±0.1</td>
<td>Active region</td>
<td></td>
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<tr>
<td>K XIII</td>
<td>6.4</td>
<td>945.83</td>
<td>(^4S_{3/2} \rightarrow ^2D_{5/2})</td>
<td>0.98±0.07</td>
<td>1.0</td>
<td>Active region</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>994.52</td>
<td>(^4S_{3/2} \rightarrow ^2D_{3/2})</td>
<td>1.8±0.1</td>
<td>1.84±0.15</td>
<td>9.60±0.1</td>
<td>Active region</td>
</tr>
<tr>
<td>Ca XIV</td>
<td>6.5</td>
<td>880.35</td>
<td>(^4S_{3/2} \rightarrow ^2D_{5/2})</td>
<td>19.2±0.3</td>
<td>1.0</td>
<td>Active region</td>
<td></td>
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<td></td>
<td></td>
<td>943.70</td>
<td>(^4S_{3/2} \rightarrow ^2D_{3/2})</td>
<td>26.8±0.3</td>
<td>1.40±0.03</td>
<td>9.05±0.2</td>
<td>Active region</td>
</tr>
</tbody>
</table>

from Si VIII to S X can be used to infer electron density in low-density plasmas, such as those observed in off disk coronal regions far from the solar surface. Ar XII, K XIII can be excellent density indicators in active regions, while Ca XIV can diagnose even denser plasma.

Electron densities measured from two distinct SUMER observations are reported in Table 1. Quiet Sun densities from different ratios are expected to be very similar since the plasma was shown to be isothermal and unstructured. Active region results on the contrary are likely to show larger variations as the emitting active region presented many individual loop-like structures along the line of sight. The results displayed in Table 1 indicate that there are several problems in the considered line ratios. In assessing these problems, we will also refer to the atomic data assessment made by [19] on a quiet Sun, off disk SUMER spectrum, which included part of the lines analyzed in the present work.

**Quiet Sun measurements:** Electron densities in the quiet Sun show a marked variability in the results of different ion and even within the two ratios of each ion. A self consistent set of electron densities is provided by the Si VIII and S X \(^4S_{2}^2D\) and P IX \(^4S_{2}^2P\) ratios, with values around \( \log N_e = 8.1 \) (\( N_e \) in \( \text{cm}^{-3} \)). This value is consistent with results from other studies ([20]) on similar emitting regions. The Al VII ratio provides only an upper limit to the electron density, which is consistent with this value.

The other ratios provide much different electron densities. The P IX \(^4S_{2}^2D\) ratio indicates an electron density around one order of magnitude larger than the previous three ratios. This might indicate the presence of a blend in the 1317.65 Å line. No indication is given in [19] as P IX was not in their assessment. The problems in the Si VIII and S X
ratios are more surprising, as no problem was indicated [19]. Since CHIANTI Version 3.02 data were used in [19], the problems should come from the new data adopted in Version 4 of the database. Collision strengths for ground forbidden transitions for both Si VIII and S X have been changed, and new R-Matrix results have been used in place of the DW data in CHIANTI Version 3.02; moreover, Si VIII atomic model has been expanded to include 72 levels from the 13 in CHIANTI Version 3.02. However, both changes to the CHIANTI Version 4.0 dataset should be improvements: as R-Matrix computations revealed the presence of resonances in collision strengths that were simply ignored by the DW calculations ([15,16]), and the presence of more excited levels brings a higher degree of completeness to the Si VIII atomic model. The two most reasonable explanations that we can give are 1) that the agreement provided by CHIANTI Version 3.02 data in [19] was misleading, or 2) the new CHIANTI Version 4.0 data show that more work is needed to reach a satisfactory atomic model for the N-like ions from AI VII to S X.

**Active Region measurements:** The Ar XII observed line ratio misses the theoretical curve, because the observed intensity of the 649.14 line is higher than predicted. This is due to a strong Si X blending line that contributes to the total intensity of the 649.14 Å line. All the other line ratios are able to provide an estimate of the electron density. If we dispense from the Ar XII 649/670 ratio, the results from active region line ratios are more in line with expectations, as they all provide electron densities similar to literature values. This confirms the great potential of the $^4S-^2D$ line ratio for density diagnostics. It is interesting to note that Ar XII and K XIII, which are formed nearly at the same temperature, provide an identical value of the electron density, confirming that they are most probably emitted by the same plasma structures. The lower value of the hotter Ca XIV line ratio may be caused by the fact that Ca XIV lines are emitted by a different plasma structure in the active region.

**ACKNOWLEDGMENTS**

A. Mohan acknowledges the financial support from the CSIR, New Delhi. E. Landi acknowledges support from the Office of Naval Research (ONR). An IAU grant enabled B.N. Dwivedi to participate and present this work in the IAU Colloquium 188.

**REFERENCES**


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