DENSITY AND TEMPERATURE DIAGNOSTICS OF SOLAR EMISSION LINES FROM Na VII AND Al IX

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(Received 21 May, 1993; in revised form 9 September, 1993)

Abstract. Line intensity ratios of EUV emission lines from Na VII and Al IX have been considered for electron density and temperature determinations within the chromosphere–corona transition region and the corona. The electron pressure within the emission region has been assumed to be a constant parameter. Theoretical line intensities for these ions have been computed using a model solar atmosphere and compared with the values as observed by ATM ultraviolet spectrometer. The observed intensities correspond to the average quiet-Sun conditions near solar minimum.

1. Introduction

Electron density and temperature measurements are of fundamental importance in probing the nature of solar atmosphere and underlying physical processes. The emission line intensity ratios from ions of different isoelectronic sequences have been extensively used to study the electron density and temperature structures in different regions of the solar atmosphere. EUV emission lines from ions of the boron sequence have been found to be good electron density indicators in the chromosphere–corona transition region and the corona (Flower and Nussbaumer, 1975a, b; Elwert and Raju, 1975; Vernazza and Mason, 1978; Dwivedi and Raju, 1980; Dwivedi, 1988; Dwivedi and Gupta, 1991a, and references cited therein). The EUV emission lines from boron-like ions Na VII and Al IX have been observed in quiet regions, active regions, coronal holes and off-limb by the ATM ultraviolet spectrometer (Vernazza and Reeves, 1978). These lines have also been observed in the sunspot plumes (Noyes *et al.*, 1985).

In a recent paper Dwivedi and Gupta (1991b) have studied only density diagnostics of Al IX $\lambda385.03/\lambda392.42$ line ratio. In this investigation we have considered the electron density and temperature diagnostics of Na VII and Al IX line ratios. We confine our attention to the observed line intensities of Na VII and Al IX pertaining to the average quiet-Sun conditions (Vernazza and Reeves, 1978). Various investigators have shown that the electron pressure within the chromosphere–corona transition region and the corona is either constant or varies rather slowly with height in the transition region and to some extent in the corona. The observed intensity of a particular Na VII line or Al IX line is due to several emitting layers.

Solar Physics **149:** 289–299, 1994.

Each layer would have different electron density and temperature values but the electron pressure would be constant or change insignificantly from layer to layer. It is, therefore, physically meaningful to study the variation of theoretical line intensity ratios with electron density (and thus temperature) at constant electron pressure. The comparison of theoretical intensity ratios with observed ratios would give the effective values of electron density and temperature within the emission regions. We have calculated theoretical intensities for several Na VII and Al IX lines using a model solar atmosphere. The computed intensities are then compared with the available observed intensities for the averaged quiet-Sun conditions at solar minimum (Vernazza and Reeves, 1978).

In Section 2, we briefly describe line emissivity. Atomic data used are explained in Section 3. Observed and theoretical line intensities are discussed in Section 4.1. Electron and temperature diagnostic aspects of line intensity ratios are examined in Section 4.2.

2. Line Emissivity

The volume emission coefficient in a radiative transition from the upper level j to a lower level i is given by

$$\epsilon(i, j) = N_j A(j, i) \frac{hc}{4\pi\lambda_{ij}} \text{ ergs cm}^{-3} \text{ s}^{-1} \text{ sr}^{-1} . \tag{1}$$

The wavelength for the transition is λ_{ij}, h is Planck's constant, c is the velocity of light, and $A(j, i)$ is the spontaneous transition probability. The number density N_j of the emitting level can be further expressed as

$$N_j(X^{+m}) = \frac{N_j(X^{+m})}{N(X^{+m})} \frac{N(X^{+m})}{N(X)} \frac{N(X)}{N(\mathrm{H})} \frac{N(\mathrm{H})}{n_e} n_e , \tag{2}$$

where X^{+m} denotes the mth ionization stage of the element X, $N_j(X^{+m})/N(X^{+m})$ is the population of level j relative to the total population of the ion X^{+m}, $N(X^{+m})/N(X)$ is the ion fraction of the ion X^{+m}. $N(X)/N(\mathrm{H})$ is the abundance of the element relative to hydrogen. We have assumed $N(\mathrm{H})/n_e = 0.8$ for the fully ionized plasma. The emissivity can be written as

$$\epsilon(i, j) = \frac{1.59 \times 10^{-8}}{4\pi\lambda_{ij}\,(\text{Å})} A(j, i) \frac{N_j(X^{+m})}{N(X^{+m})} \frac{N(X^{+m})}{N(X)} \frac{N(X)}{N(\mathrm{H})} n_e . \tag{3}$$

We denote the observed line emission as

$$I(\lambda_{ij}) = 1.265 \times 10^{-9} \int \epsilon^*(i, j) n_e dh(\text{cm}) \text{ ergs cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1} , \tag{4}$$

where

$$\epsilon^*(i,\, j) = \frac{A(j,\, i)}{\lambda_{ij}\ (\text{Å})} \frac{N_j(X^{+m})}{N(X^{+m})} \frac{N(X^{+m})}{N(X)} \frac{N(X)}{N(\text{H})} \,. \tag{5}$$

The intensity ratio of two lines emitted from the same ion can be expressed as

$$\frac{I(\lambda_{ij})}{I(\lambda_{kl})} = \frac{A(j,\, i)}{A(l,\, k)} \frac{\lambda_{kl}}{\lambda_{ij}} \frac{N_j(X^{+m})}{N_l(X^{+m})} \,. \tag{6}$$

We have solved the steady-state equations for the various levels to obtain the number density for the emitting levels as a function of electron density and temperature. Electron density and temperature values are restricted by the constant electron pressure parameter ($n_e T$). The first 11 lowermost levels have been considered for the ions Na VII and Al IX.

3. Atomic Data

The atomic data needed to compute line intensities are the following: (i) wavelengths, (ii) the radiative transition probabilities, and (iii) collision strengths. The wavelengths for Na VII and Al IX have been taken from Kelly and Palumbo (1973) and Wiese, Smith, and Miles (1969). Some wavelengths were estimated with the help of other known wavelengths.

The spontaneous transition probabilities for O IV, Na VII, Si X, and S XII (Flower and Nussbaumer, 1975a, b) of a particular transition were plotted against the residual charge on the ions. A smooth curve was drawn through the various points. The graphical value was used for a given transition of Na VII and Al IX. Collision strengths for the various transitions of Na VII and Al IX were obtained in a manner similar to that of spontaneous transition probabilities.

4. Results and Discussion

4.1. Observed and Theoretical Intensities

Na VII *lines*: The Na VII ion has two close lines, one at 491.95 Å and the other at 491.86 Å. The line at 491.95 Å is the strongest of the two. Their combined theoretical intensity is close to the observed value quoted by Vernazza and Reeves (1978). The observed intensity has statistical fluctuation exceeding 10%.

The line at 486.74 Å has observed value which is about 6 times the computed intensity. The discrepancy could be due to blending by unknown strong lines.

Vernazza and Reeves (1978) have listed an observed line at 352.6 Å with an intensity of 160 ergs cm^{-2} s^{-1} sr^{-1}. They attribute this line, with probable identification status, to Ar XVI line at 353.8 Å and Fe XIV at 353.8 Å. Na VII has a line at 353.29 Å with an observable intensity of 2.21 ergs cm^{-2} s^{-1} sr^{-1}. This Na VII line would blend with Fe XI line at 352.68 Å, Mg V lines at 352.20 Å, 353.09 Å, and 353.30 Å. The Mg V line at 353.09 Å has theoretical intensity of

TABLE I
Line intensities of Na VII lines ($N(\mathrm{Na})/N(\mathrm{H}) = 2.88 \times 10^{-6}$)

Transition $2s2p^2 \rightarrow 2s^22p$	Wavelength[a] (Å)	Intensities (ergs cm^{-2} s^{-1} sr^{-1}) Computed	Observed[c]
$^2D_{5/2} - ^2P^0_{3/2}$	491.95	1.52	1.12
$^2D_{3/2} - ^2P^0_{3/2}$	491.86	0.15	
$^2D_{3/2} - ^2P^0_{1/2}$	486.74	0.87	5.14
$^2S_{1/2} - ^2P^0_{3/2}$	381.30	0.67	
$^2S_{1/2} - ^2P^0_{1/2}$	378.22	0.43	
$^2P_{1/2} - ^2P^0_{3/2}$	354.95	0.47	
$^2P_{3/2} - ^2P^0_{3/2}$	353.29	2.21	160[d]
$^2P_{1/2} - ^2P^0_{1/2}$	352.28	0.84	
$^2P_{3/2} - ^2P^0_{1/2}$	350.65	0.44	
$^4P_{5/2} - ^2P^0_{3/2}$	870.72[b]	0.074	
$^4P_{3/2} - ^2P^0_{3/2}$	878.88[b]	0.044	

[a] Kelly and Palumbo (1973).
[b] Estimated.
[c] Vernazza and Reeves (1978).
[d] Cf. text.

4.32 ergs cm^{-2} s^{-1} sr^{-1} (Raju and Dwivedi, 1978). Future observations at high spectral resolutions are needed to resolve these blends.

In Table I we have listed the computed intensity of various Na VII lines. Available observed intensities are also tabulated. Theoretical intensities in column 3 have been obtained by assuming: (i) spherically-symmetric model solar atmosphere (Elzner, 1976), (ii) density-dependent ion fractions calculated by Landini and Fossi (1972), and (iii) the value of 2.88×10^{-6} for the element abundance of Na (Withbroe, 1976). We have calculated, in addition, intensities using (a) low-density ion fractions published by Arnaud and Rothenflug (1985), (b) low-density ion fractions tabulated by Landini and Fossi (1972). In the case of (a) computed itensities are smaller by 15% than the density-dependent case. In the case of (b) the computed values are larger by about 15% than the density-dependent case.

Al IX *lines*: Al IX has two lines very close to each other around 392.4 Å. Vernazza and Reeves have observed a line at 392.3 Å and identified it with Al IX line at 392.4 Å with an intensity of 16.29 ergs cm^{-2} s^{-1} sr^{-1} and a statistical error exceeding 10%. The computed intensity is about an order of magnitude smaller than the observed intensity. This discrepancy has to be attributed to some unknown strong lines.

The observed line at 385.0 Å has been identified as Al IX 385.0 Å line by Vernazza and Reeves. The observed intensity is 38.07 ergs cm^{-2} s^{-1} sr^{-1} with statistical uncertainty exceeding 10%. The computed intensity at 384.95 is about

TABLE II
Line intensities of Al IX lines ($N(\text{Al})/N(\text{H}) = 2.95 \times 10^{-6}$)

Transition $2s2p^2 \rightarrow 2s^22p$	Wavelength[a] (Å)	Intensities (ergs cm^{-2} s^{-1} sr^{-1}) Computed	Observed[c]
$^2D_{5/2} - ^2P^0_{3/2}$	392.40	1.48	16.29[d]
$^2D_{3/2} - ^2P^0_{3/2}$	392.33	0.23	
$^2D_{3/2} - ^2P^0_{1/2}$	384.95	1.59	38.07[d]
$^2S_{1/2} - ^2P^0_{3/2}$	305.10	0.82	
$^2S_{1/2} - ^2P^0_{1/2}$	300.60	0.79	
$^2P_{1/2} - ^2P^0_{3/2}$	286.45	0.94	
$^2P_{3/2} - ^2P^0_{3/2}$	284.04	2.89	
$^2P_{1/2} - ^2P^0_{1/2}$	282.45	1.28	
$^2P_{3/2} - ^2P^0_{1/2}$	280.16	0.57	
$^4P_{5/2} - ^2P^0_{3/2}$	686.81[b]	0.071	
$^4P_{3/2} - ^2P^0_{3/2}$	698.76[b]	0.052	

[a] Kelly and Palumbo (1973).
[b] Estimated.
[c] Vernazza and Reeves (1978).
[d] Cf. text.

24 times smaller than the observed value. There is the possibility of the intersystem transition of C III at 385.04 Å blending with the Al IX line at 384.95 Å. In Table II we have listed the computed intensity for vairous Al IX lines. Observed intensities as quoted by Vernazza and Reeves are also tabulated. Al IX lines at 305.10, 300.6, 286.45, 284.04, and 282.45 Å have observable intensities. It should be possible to observe them at high spectral resolutions. Theoretical intensities have been computed by assuming the value 2.95×10^{-6} for the element abundance of Al (Withbroe, 1976). Other assumptions are the same as for Na VII. Moreover, we have computed Al IX line intensities using: (a) low-density ion fractions tabulated by Arnaud and Rothenflug (1985), and (b) low-density ion fractions computed by Landini and Rossi (1972). In the case (a) computed intensities are less by 20% than that of high-density case. In case (b) the computed values are less by 4% than the high-density case.

4.2. Electron Density and Temperature Diagnostics

EUV emission lines from boron-like ions Ne VI, Mg VIII, Si X, and S XII have been used earlier to determine electron densities in the solar atmosphere. To our knowledge emission lines of Na VII have not been considered for plasma diagnostics. Dwivedi and Gupta (1991b) have considered only density diagnostics of the Al IX λ385.03/392.42 line ratio. Here we consider, in some detail, electron density and temperature determinations using Na VII and Al IX line intensity ratios.

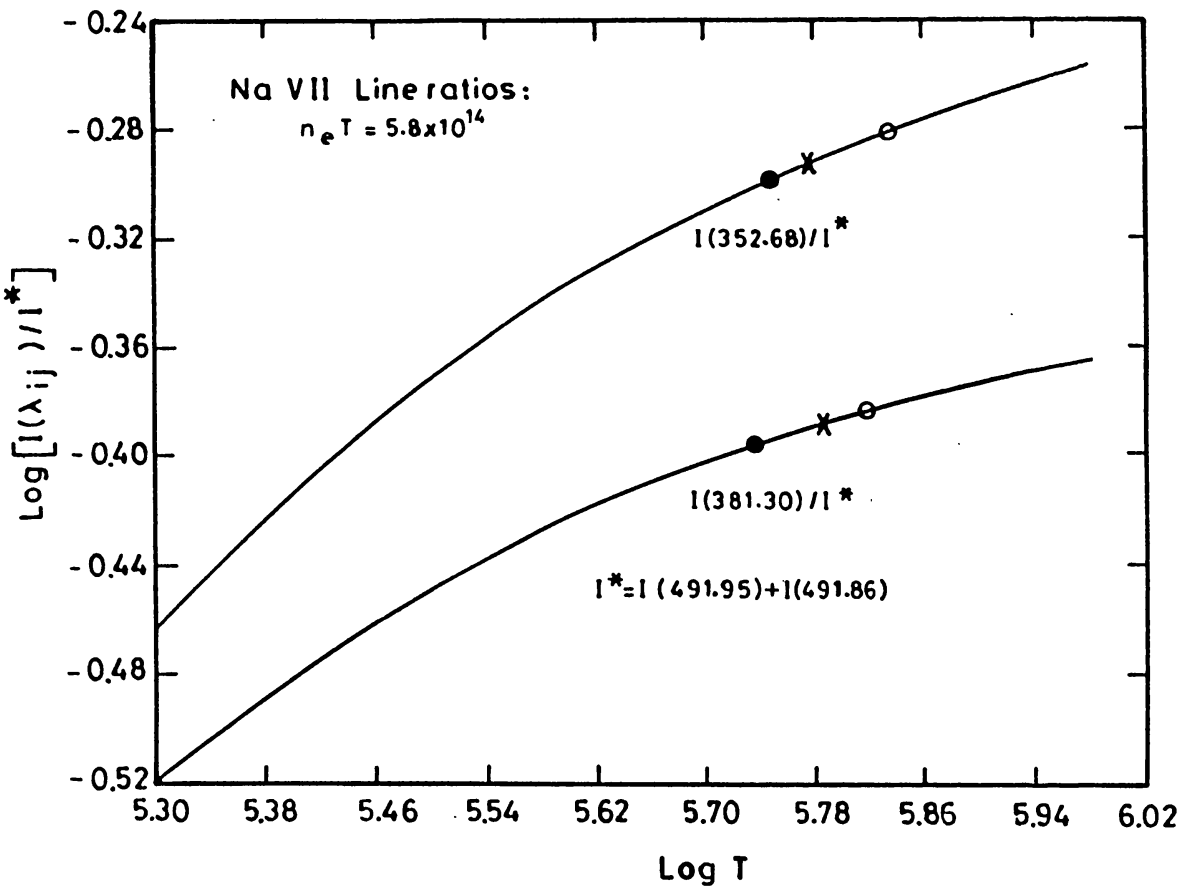

Fig. 1. Line intensity ratios for Na VII lines as a function of electron temperature for a constant electron pressure parameter $n_e T$ ($= 5.8 \times 10^{14}$). The filled circles represent theoretical intensity ratios using density-dependent ion fractions (Landini and Fossi, 1972). The open circles correspond to low density case (Landini and Fossi, 1972). The crosses refer to the case using low-density ion fractions tabulated by Arnaud and Rothenflug (1985).

Various investigations have shown that the electron pressure within the chromosphere–corona transition region and the corona is either constant or varies rather slowly with height in the transition region and to some extent in the corona. We have, therefore, calculated several line intensity ratios as a function of electron density and temperature and keeping the electron pressure constant. This procedure is meaningful because the observed intensity of a particular Na VII or Al IX line refers to the average physical conditions of the emitting layers within which electron densities and temperatures vary but the electron pressure remains practically constant. Thus, we will get the effective electron density and the corresponding temperature from a particular line intensity ratio. This approach was first used for the emission lines of Ne VI and Mg VI (Raju and Gupta, 1993). According to the model atmosphere used in the present study we find that the layers which contribute to Na VII line intensities have electron density and temperature values varying by a factor of three but the electron pressure varies by 14% only. In the case of Al IX lines 75% of the intensity is due to layers within which temperature changes by a factor of 2

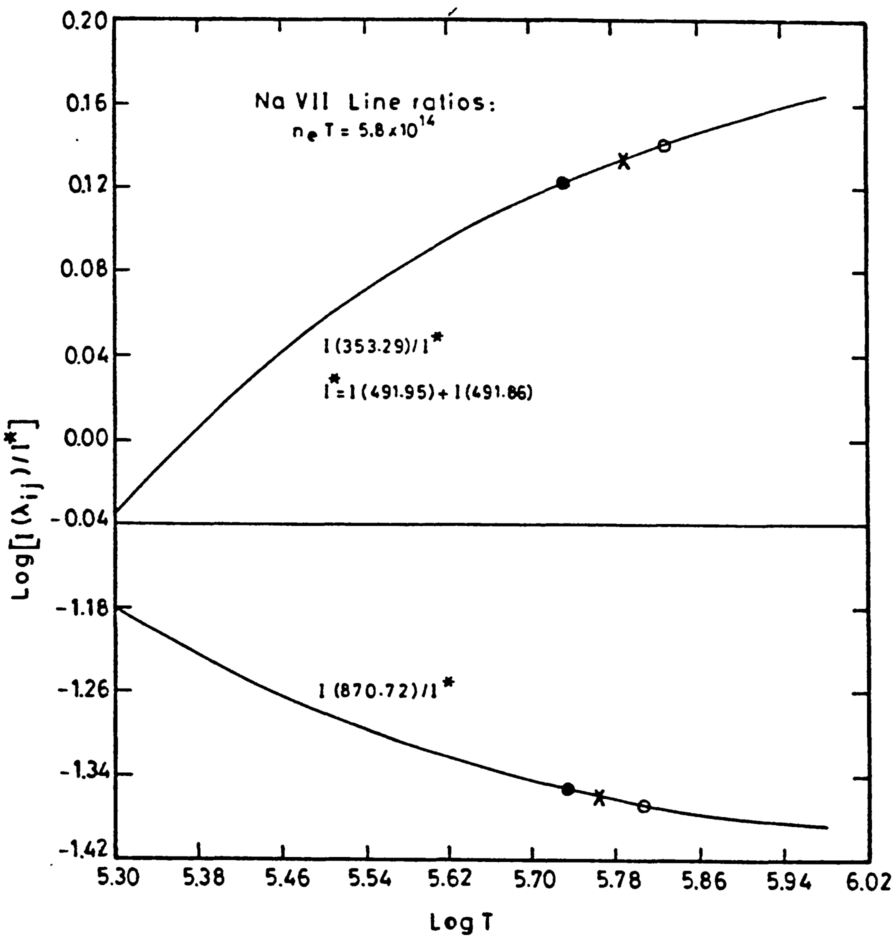

Fig. 2. Same as Figure 1 for other Na VII lines.

and the electron density by a factor of 2.55, but the electron pressure changes by 24%. The balance of 25% of an Al IX line intensity is from layers within which temperature changes by a factor of 1.34 and the electron density by a factor of 3, but the electron pressure varies by a factor of 2.3. Due to lack of reliable observed intensities for Na VII and Al IX lines we have considered here only the theoretical line intensity ratios obtained by using a model atmosphere. These theoretical line intensity ratios have been used, for the sake of illustration, to infer effective electron densities and the corresponding temperatures within the emitting regions which give rise to Na VII and Al IX lines. The derived effective electron temperatures from the various line ratios would be, on account of the basic assumption of constant electron pressure, different from the respective temperatures at which the ions Na VII and Al IX attain maximum abundance.

Future space observations at high spectral resolutions are, therefore, essential for using the Na VII and Al IX theoretical line intensity ratios for the purposes of reliable electron density and temperature diagnostics.

TABLE III
Electron densities and temperatures derived from Na VII line ratios

λ'(Å)/λ(Å)	n_e (cm^{-3})	T(K)
381.30/491.90	1.07×10^9	5.42×10^5
353.29/491.90	1.08×10^9	5.35×10^5
352.68/491.90	1.04×10^9	5.57×10^5
870.72/491.90	1.07×10^9	5.42×10^5

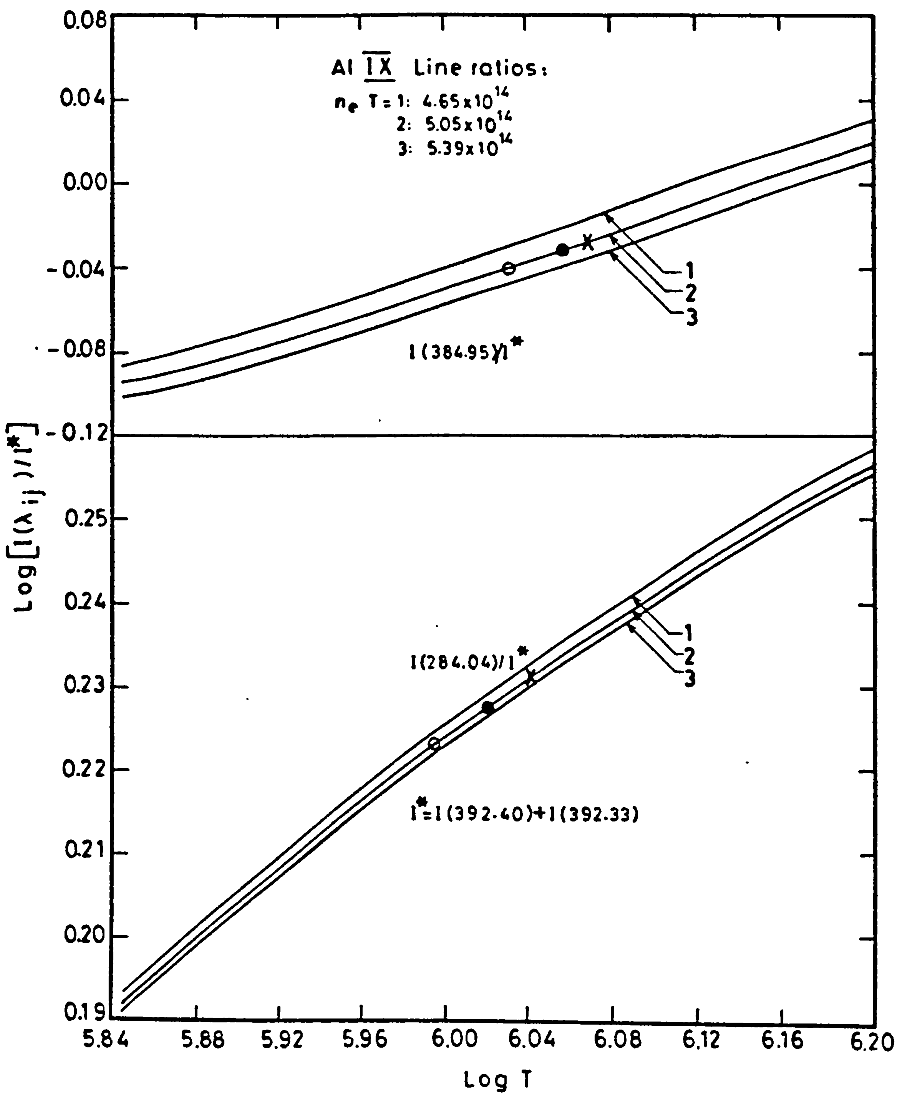

Fig. 3. Same as Figure 1 but for Al IX. Theoretical ratios are indicated for the pressure parameter n_eT ($= 5.05 \times 10^{14}$). The curves 1 and 3 are for the pressure parameters 4.65×10^{14} and 5.39×10^{14}, respectively.

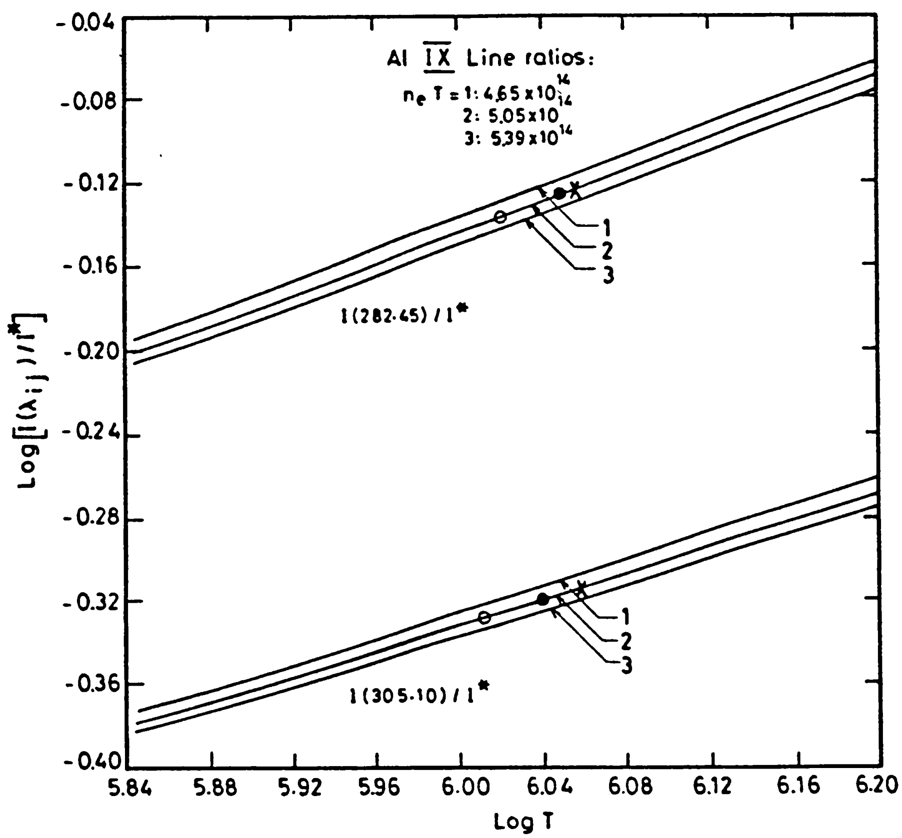

Fig. 4. Same as Figure 3 for other Al IX lines.

TABLE IV
Electron densities and temperatures derived from Al IX line ratios

λ′(Å)/λ(Å)	n_e (cm^{-3})	T(K)
384.95/392.36	4.43×10^8	1.14×10^6
305.10/392.36	4.63×10^8	1.09×10^6
284.04/392.36	4.81×10^8	1.05×10^6
282.45/392.36	4.55×10^8	1.11×10^6

4.2.1. Intensity Ratios Using Na VII *Lines*

In Figures 1 and 2, we have shown the variation of theoretical line intensity ratios as a function of electron temperature. The corresponding electron density is given by the constant electron pressure parameter (n_eT). We have combined the two very close lines at 491.86 and 491.95 Å to constitute the reference line for the line ratios. A value of 5.8×10^{14} (cm^{-3} K) has been adopted for the electron pressure parameter (n_eT). At this value Na VII lines attain 50% of their full intensity values. The filled circles represent the theoretical ratios obtained by using density-dependent ion fractions tabulated by Landini and Fossi (1972). The open circles correspond to low-density case (Landini and Fossi, 1972) and the crosses refer to the case using ion fractions tabulated by Arnaud and Rothenflug (1985). In Table III we have listed some of the line ratios and the derived effective electron densities and the corresponding electron temperatures for the case of density-dependent ion fractions. We notice that different line ratios give different electron densities and temperatures. This is due to the fact that, apart from the density sensitivity of line ratios, line ratios contain a sensitive exponential factor involving line wavelengths and the temperature.

4.2.2. *Intensity Ratios Using Al* IX *Lines*

In Figures 3 and 4 we have shown the variation of theoretical line intensity ratios against temperature. The electron density is given by the electron pressure parameter. For the reference line we have combined the two very close lines at 392.33 and 392.40 Å. The filled circles represent theoretical ratios using the density-dependent ion fractions (Landini and Fossi, 1972). The open circles correspond to the case using low-density ion fractions (Landini and Fossi, 1972). The crosses refer to the case based on low-density ion fractions tabulated by Arnaud and Rothenflug (1985). We have considered three values for the electron pressure parameter. The value of 4.65×10^{14} (cm^{-3} K) corresponds to the atmospheric layer at which 75% of the full intensity value is obtained. The value of 5.05×10^{14} (cm^{-3} K) refers to the level at which 50% of the full intensity value is reached. The level at which 25% of the full intensity is obtained, the electron pressure parameter has a value of 5.39×10^{14} (cm^{-3} K). In Table IV we have listed the line ratios and the derived effective electron densities and the corresponding electron temperatures. They are for the case of density-dependent ion fractions with the pressure parameter having a value of 5.05×10^{14} (cm^{-3} K). The electron density and temperature values are different for different Al IX line ratios. The explanation for these different values is the same as in the case of Na VII line ratios.

5. Conclusion

We have seen that, under the assumption of constant electron pressure, the EUV emission lines from Na VII and Al IX can be used for simultaneous determination of electron density and temperature within the chromosphere–corona transition region and the corona. Our analysis of Na VII and Al IX line intensities for the averaged quiet-Sun conditions suggests the need for future observations at higher spectral resolutions to facilitate more detailed electron density and temperature diagnostics of the chromosphere–corona transition region and the solar corona. This will become available from the CDS and the SUMER instruments on SOHO schedule for launch in 1995 by ESA/NASA.

Acknowledgements

The authors are grateful to the learned referee for encouraging remarks and valuable suggestions.

References

Arnaud, M. and Rothenflug, R.: 1985, *Astron. Astrophys. Suppl.* **60**, 425.
Dwivedi, B. N.: 1988, *Solar Phys.* **116**, 405.
Dwivedi, B. N. and Gupta, A. K.: 1991a, *Adv. Space Res.* **11**, No. 1, 307.
Dwivedi, B. N. and Gupta, A. K.: 1991b, *Solar Phys.* **135**, 415.
Dwivedi, B. N. and Raju, P. K.: 1980, *Solar Phys.* **68**, 111.
Elwert, G. and Raju, P. K.: 1975, *Astrophys. Space Sci.* **38**, 369.
Elzner, L. R.: 1976, *Astron. Astrophys.* **47**, 9.
Flower, D. R. and Nussbaumer, H.: 1975a, *Astron. Astrophys.* **45**, 145.
Flower, D. R. and Nussbaumer, H.: 1975b, *Astron. Astrophys.* **45**, 349.
Kelly, R. L. and Palumbo, L. J.: 1973, *Atomic and Ionic Emission Lines below 2000 Å*, NRL Report 7599.
Landini, M. and Monsignori Fossi, B. C.: 1972, *Astron. Astrophys. Suppl.* **7**, 291.
Noyes, R. W., Raymond, J. C., Doyle, J. G., and Kingston, A. E.: 1985, *Astrophys. J.* **297**, 805.
Raju, P. K. and Dwivedi, B. N.: 1978, *Solar Phys.* **60**, 269.
Raju, P. K. and Gupta, A. K.: 1993, *Solar Phys.* **145**, 241.
Vernazza, J. E. and Mason, H. E.: 1978, *Astrophys. J.* **226**, 720.
Vernazza, J. E. and Reeves, E. M.: 1978, *Astrophys. J. Suppl.* **37**, 485.
Wiese, W. L., Smith, M. W., and Miles, B. M.: 1969, *Atomic Transition Probabilities*, Vol. 2, *Sodium through Calcium*, U.S. Dept. of Commerce, Washington, D.C.
Withbroe, G. L.: 1976, Center for Astrophysics preprint No. 524.