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DENSITY DEPENDENCE OF SOLAR EMISSION LINES OF OXYGEN-LIKE IONS*

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Abstract. Assuming steady state conditions, the occupation of 9 levels of oxygen-like ions: Ne III, Mg V, Si VII, S IX, and Ar XI have been computed as a function of electron density and temperature. The following physical processes have been considered: collisional excitations and spontaneous radiative de-excitations for permitted and intercombination transitions; collisional excitations and de-excitations, photo-excitations and spontaneous radiative transitions among the five levels of the ground term. This study indicates that line intensity ratios for oxygen-like ions can be used as a diagnostic in the determination of these two parameters of the solar plasma.

1. Introduction

The physical state, for instance, electron density, temperature, and excitation conditions of the solar atmosphere can be best understood from an analysis and interpretation of its emission line spectrum. A rigorous analysis of emission lines requires knowledge of atomic parameters and the solution of the equations of statistical equilibrium for level populations over pertinent ranges of electron density and temperature.

Line emission from Be I-like ions has so far received most attention for direct determinations of electron density in the solar atmosphere (Munro *et al.*, 1971; Jordan, 1971; Gabriel and Jordan, 1972; Loulergue and Nussbaumer, 1976). In addition to Be I-like ions, detailed investigations have also been made of line emission from Al I-like (Blaha, 1971), B I-like (Elwert and Raju, 1975; Flower and Nussbaumer, 1975a, b), and N I-like ions (Raju, 1978). Lines emitted from ions of these iso-electronic sequences have proved to be a useful probe for the determination of the electron density in the emission regions of the solar atmosphere. In the present investigation lines emitted from O I-like ions have been considered as a possible indicator of electron density in the emitting region. In view of their large elemental abundances, the ions considered are: Ne III, Mg V, Si VII, S IX, and Ar XI. According to the ionization equilibrium calculations of Jordan (1969) and Landini

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and Fossi (1972), Ne III has maximum relative ion abundance at 6×10^4 K, Mg V at 2.5×10^5 K, Si VII at 5×10^5 K, S IX at 10^6 K, and Ar XI at 2×10^6 K. Thus, the study of line emission from these ions is of interest for probing the solar chromosphere-corona transition region and the corona.

The various physical processes which govern line emission, in the present context, are: electron collisional excitations and spontaneous radiative de-excitations for permitted and intercombination transitions; electron collisional excitations and de-excitations, photo-excitations and spontaneous radiative transitions among the ground term levels. The radiative excitation rates for the permitted transitions have been neglected since the lines corresponding to these transitions are in the EUV regions of the spectrum and are optically thin. Moreover, at the temperatures of interest, recombinations for the levels considered have been neglected compared to the electron excitations. Due to lack of appropriate data, proton collisional transitions among the ground term levels have also been neglected.

2. Energy Level Scheme and Atomic Data

For computing various line intensities we have, for the sake of simplicity, restricted our attention to transitions taking place between the first nine levels of these ions. All these transitions have wavelengths greater than 100 Å. In Figure 1 we have shown

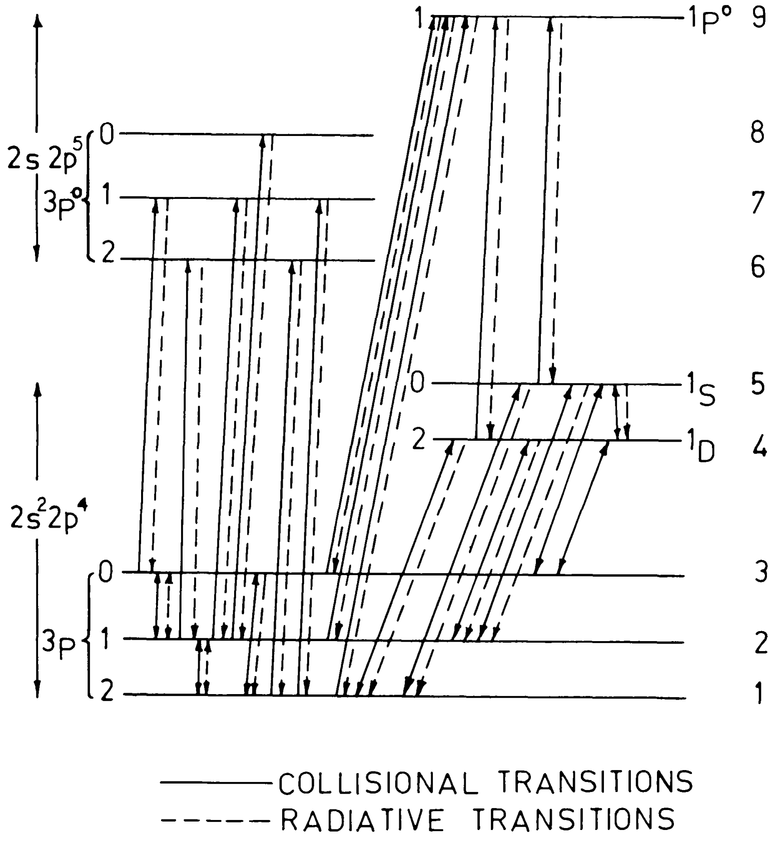

Fig. 1. Level scheme for oxygen-like ions.———collisional transitions;------radiative transitions.

schematically the adopted energy levels. The ground configuration consists of a triplet P, a singlet D, and a singlet S term whereas higher configuration forms a triplet P and a singlet P term. Various transitions considered in the present computation are as indicated in Figure 1.

The atomic data needed for detailed computation of line intensities have been taken from various sources. Allowed transition probabilities for the above ions have been taken from Safronova (1975). The data for the forbidden transitions have been taken from the tabulation of Wiese *et al.* (1966, 1969) and Kastner *et al.* (1977). Using the transition probabilities given by Safronova (1975), we have calculated the respective absorption oscillator strengths, f_{ij}, for the permitted lines. These calculated f_{ij} values for Ne III, Mg V, Si VII and S IX compare well with reported values (Wiese *et al.*, 1966, 1969; Malinovsky and Heroux, 1973). The transition probabilities for the transitions ${}^1P^0$-${}^3P$ have been estimated by extrapolation using the values for higher ions of oxygen sequence (Safronova, 1975). Wavelength values have been taken from various sources (Edlén, 1972; Fawcett and Gabriel, 1964; Kelly and Palumbo, 1973).

Collision strengths, $\Omega(i, j)$, for Ne III and Mg V for the transitions ${}^3P_2$-${}^3P_1$, ${}^3P_2$-${}^3P_0$, and ${}^3P_1$-${}^3P_0$ have been taken from Blaha (1969). In order to estimate the collision strengths for the other fine structure transitions for these two ions we have used the values for the appropriate multiplet collision strengths given by Czyzak *et al.* (1968) and the relations

$$\Omega({}^1S,{}^3P_J) = \tfrac{1}{9}(2J+1)\Omega({}^1S,{}^3P)\,,$$

$$\Omega({}^1D,{}^3P_J) = \tfrac{1}{9}(2J+1)\Omega({}^1D,{}^3P)\,,$$

given by Saraph *et al.* (1969). Collision strengths for S IX and Ar XI have been taken from Czyzak *et al.* (1974). In case of Si VII ion $\Omega(i, j)$ values have been obtained by interpolation. Collision strengths for the intercombination transitions ${}^3P$-${}^1P^0$ have been estimated using the computed values for Ca XIII (Mason, 1975) by scaling along the iso-electronic sequence. The scaling was done by multiplying the collision strengths for Ca XIII by a factor $Z^2(\text{Ca XIII})/Z^2(\text{ion})$, where Z is the residual charge on the ion.

Photo-excitation rates, R_{ij}, have been considered only for the transitions ${}^3P_2$-${}^3P_1$ and ${}^3P_1$-${}^3P_0$. For the other transitions photo-excitation rates are not significant. The rates R_{ij} used in the present study have been obtained using the expression

$$R_{ij} = \frac{\omega_j}{\omega_i} A_{ji}\left(e^{h\nu_{ij}/KT_r} - 1\right)^{-1} W\,,$$

where W is the dilution factor, ω's statistical weight, A_{ji} spontaneous transition probability, ν_{ij} the frequency of the transition, and T_r is the radiation temperature corresponding to the particular transition. The dilution factor has been assumed to be equal to 0.5 in all cases for the sake of simplicity in computation. For estimating R_{ij}

we have calculated T_r, knowing the continuum flux at a given wavelength, with the help of mean solar black body emission formula

$$J_\nu = \frac{2h\nu^3}{c^2}(e^{h\nu/KT_r} - 1)^{-1} .$$

3. Line Emission

The line emission from a given volume element in the solar atmosphere in a steady state is given by the expression

$$E(j, i) = \frac{1}{4\pi} A_{ji}\, h\nu_{ij}\, N_j \text{ (ergs cm}^{-3}\text{ s}^{-1}\text{ sr}^{-1}) ,$$

where N_j is the level density for the upper level of the transition. The most important quantity in the computation of line emission is N_j. Assuming steady state condition, we have solved the statistical equilibrium equations for various levels with the electron density and temperature as parameters. Equilibrium equation for a given level (j) can be expressed as

$$N_j\left[\sum_{i<j}(A_{ji} + N_e C_{ji}) + \sum_{k>j} N_e C_{jk}\right] =$$

$$= \sum_{i<j} N_i[R_{ij} + N_e C_{ij}] + \sum_{k>j} N_k[A_{kj} + N_e C_{kj}] .$$

N_e is the electron density, and C's are the collisional rates. Collisional rates are expressed in terms of collision strengths Ω (i, j) in the form

$$C_{ij} = 8.63 \times 10^{-6}\, \Omega(i, j) \exp(-E_{ij}/KT_e)/\omega_i T_e^{\frac{1}{2}} \text{ (cm}^{-3}\text{ s}^{-1}) \quad \text{(for excitations)},$$

$$C_{kj} = C_{jk}\frac{\omega_j}{\omega_k}\exp(E_{jk}/KT_e) \text{ (cm}^{-3}\text{ s}^{-1}) \quad \text{(for de-excitations)}$$

where T_e is the electron temperature, K the Boltzmann constant, and E_{ij} is the excitation energy. Collisional rate for the allowed transitions is expressed in terms of absorption oscillator strengths as (van Regemorter, 1962)

$$C_{ij} = 1.70 \times 10^{-3} f_{ij} g \exp(-E_{ij}/KT_e)/E_{ij}(\text{ev}) T_e^{\frac{1}{2}} \text{ (cm}^{-3}\text{ s}^{-1}) ,$$

where f_{ij} is the oscillator strength and g is the Gaunt factor. In order to simplify computations we have assumed Gaunt factor to be equal to 0.8 for all the permitted transitions considered. This is reasonable for the allowed transitions which do not inolve a change in the principal quantum number.

Since the occupation of higher levels is essentially determined by the ground term levels, the variation of the population of these levels with electron density will be reflected in the variation of line emission with electron density. Further, since the variation of relative ion abundance of an element exhibits sharply peaked behaviour with respect to temperature, it is reasonable to assume that line emission takes place from a layer of effectively uniform density and temperature. In Figures 2 and 3 we have shown line intensity ratios as a function of electron density for each of Mg v, Si vii, S ix, and Ar xi. The temperature values indicated in these figures are those at which the relative ion abundance of the element is maximum. We have also studied Ne iii lines but they are not useful as density indicators because of their formation at the high electron density of $3 \times 10^{10}\,\mathrm{cm}^{-3}$. At this density the collisional de-excitation rates among the ground term levels are much larger than the corresponding radiative rates. Consequently, in this case the populations of the ground term levels become insensitive to the variation in electron density.

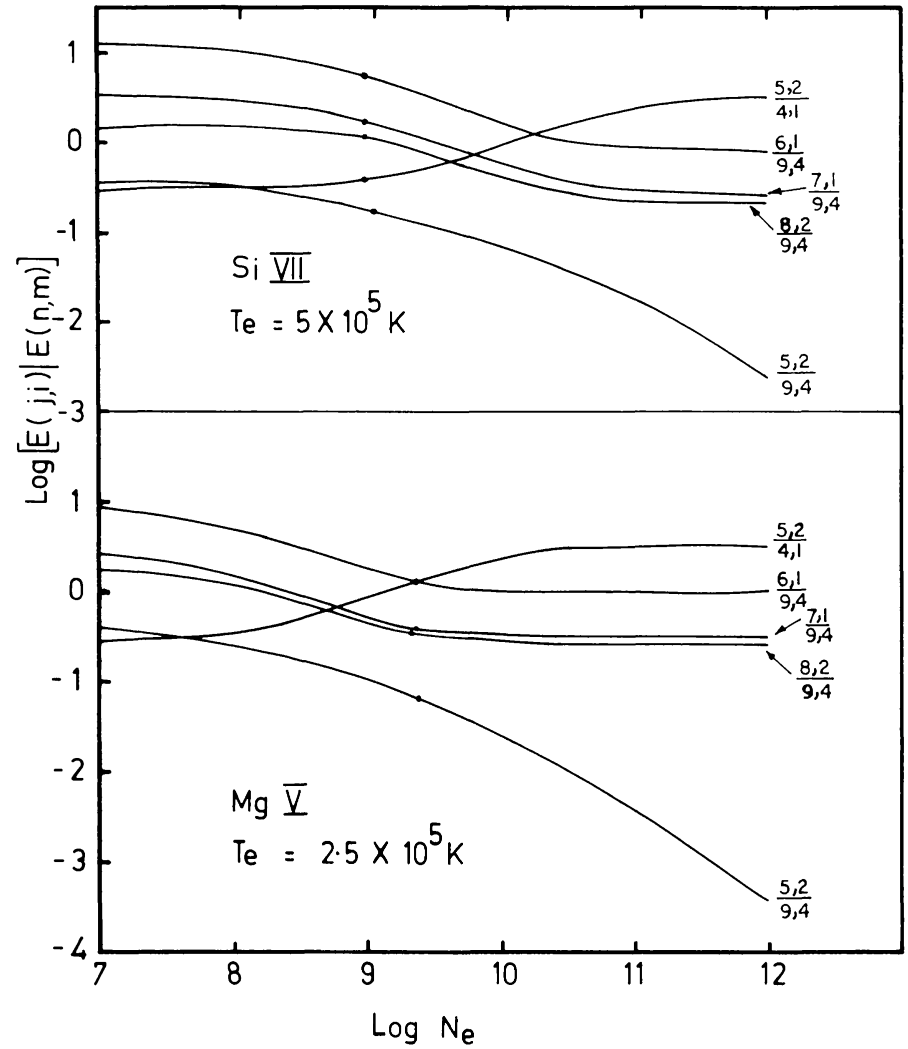

Fig. 2. Intensity ratios $E(j, i)/E(n, m)$ as a function of N_e. Dots correspond to the calculated intensity ratios based on the model of Elzner (1976). T_e corresponds to the temperature for the maximum relative ion abundance of the element.

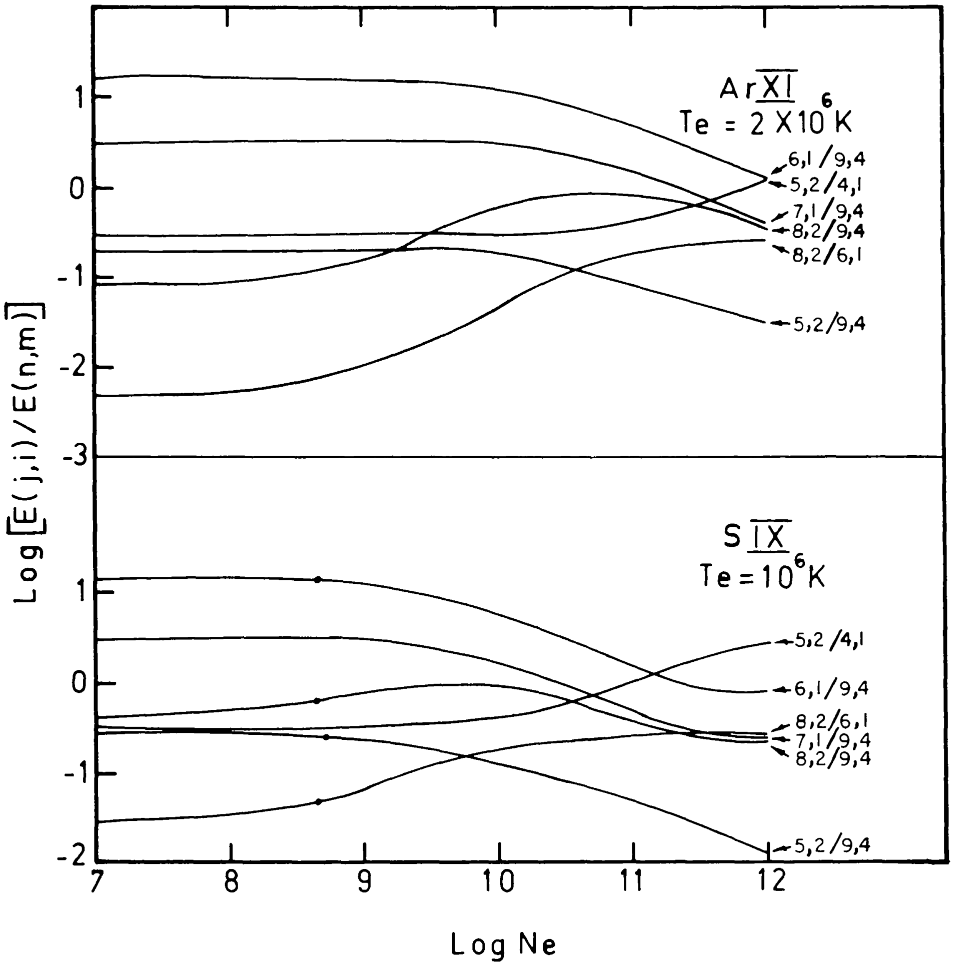

Fig. 3. Same as Figure 2.

4. Results and Discussion

There are very few observed lines from these ions with calibrated intensities suitable for density determinations. To check whether the density sensitivity of our line ratios falls into a range useful for solar work, we have calculated the relevant intensity ratios using a spherically symmetric model for the quiet Sun (Elzner, 1976). The ratios thus obtained are shown by dots in Figures 2 and 3. They fall on the density sensitive portion of the curves, thereby providing a direct method for determining N_e. In case of Ar XI lines, we cannot assign a definite value for electron density because the transition region and corona equally contribute to the fluxes for these lines.

From Figures 2 and 3 we notice that the forbidden line intensity with the transition ${}^1S_0$-${}^3P_1$ relative to the allowed singlet line (9, 4) with the transition (${}^1P_1^0$-${}^1D_2$) would, in particular, serve as a useful indicator of electron density for active regions. Recently, Sandlin *et al.* (1977) have observed in two active regions off the limb, lines corresponding to the forbidden transitions ${}^1S_0$-${}^3P_1$ of Mg V and ${}^1D_2$-${}^3P_2$ of Si VII, S IX, and Ar XI. For the two active regions Sandlin *et al.* (1977) quote the following intensity values, relative to the Fe XII line at 1242 Å, for the above mentioned forbidden transitions: 2 for Si VII line at 2146.64 Å and 1.2 for S IX line at 1715.44 Å for the active region AR 12114 at 4″ above the limb; 0.09 for Mg V line at 1324.44 Å, 0.50 for S IX line at 1715.44 Å, and 0.10 for Ar XI line at 1392.12 Å for the active region AR 12300 at 40″ above the limb. The Mg V line corresponds to the transition ${}^1S_0$-${}^3P_1$ whereas Si VII, S IX, and Ar XI lines correspond to the transition ${}^1D_2$-${}^3P_2$. In the view of the intensity ratios discussed above, lines corresponding to the transition ${}^1S_0$-${}^3P_1$ of Si VII, and S IX must definitely be observable in active regions. The corresponding line of Ar XI would be faint. Moreover, for S IX forbidden line at 1.25 μ with the transition ${}^3P_1$-${}^3P_2$ should have observable flux in active regions.

In Tables I and II we have listed calculated fluxes from the entire solar disk at Earth's distance for various strong and weak lines. Calculated fluxes for these lines may prove useful in resolving the difficulties associated with line identification, masking or blending due to lines arising from ions belonging to other isoelectronic sequences. The fluxes were calculated using the spherically symmetric model for the quiet Sun (Elzner, 1976). The relative abundance values for Mg, Si, and S have been taken from Kato (1976) and in the case of Ar from Allen (1973). With longer exposures it should be possible to observe some of the weaker lines also, in particular across the solar limb. Calculated fluxes for some of the lines are comparable with those reported by Malinovsky and Heroux (1973). In the extreme cases they agree within a factor of two. The discrepancies in the calculated and observed flux values could be ascribed to uncertainties in atomic parameters, relative abundances, and the model atmosphere. There are no observationaal data available for Mg V. On the basis of our computation, there are several lines with observable intensity (Table I).

TABLE I

Calculated fluxes from the entire solar disk at Earth's distance

Transition	Mg V-ion; $n(\text{Mg})/n(\text{H}) = 3.16 \times 10^{-5}$			Si VIII-ion; $n(\text{Si})/n(\text{H}) = 5.01 \times 10^{-5}$		
	λ (Å)	Flux (10^{-3} ergs cm^{-2} s^{-1})		λ (Å)	Flux (10^{-3} ergs cm^{-2} s^{-1})	
		Calculated	Observed		Calculated	Observed
(9, 4)	276.58	0.46	–	217.83	0.47	–
(7, 1)	351.09	0.18	–	272.64	0.80	0.70
(8, 2)	352.20	0.16	–	274.18	0.55	m
(6, 1)	353.09	0.59	–	275.35	2.68	2.0
(7, 2)	353.30	0.11	–	275.67	0.46	0.03
(7, 3)	354.22	0.15	–	276.84	0.60	0.5
(6, 2)	355.33	0.19	–	278.45	0.86	m
(5, 2)	1324.42	0.03	–	1049.26	0.08	–
(4, 1)	2784.03	0.02	–	2147.75	0.21	–

Observed values are from Malinovsky and Heroux (1973).
m denotes that the line is masked.

TABLE II

Calculated fluxes from the entire solar disk at Earth's distance

Transition	S IX-ion; $n(\mathrm{S})/n(\mathrm{H}) = 1.99 \times 10^{-5}$			Ar IX-ion; $n(\mathrm{Ar})/n(\mathrm{H}) = 6.31 \times 10^{-6}$		
	λ (Å)	Flux (10^{-3} ergs $\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$)		λ (Å)	Flux (10^{-3} ergs $\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$)	
		Calculated	Observed		Calculated	Observed
(9, 4)	179.32	0.15	–	151.86	0.03	–
(7, 1)	221.26	0.48	1.3	184.51	0.10	–
(8, 2)	223.27	0.09	0.9	187.08	0.003	–
(6, 1)	224.75	2.03	3.3	188.82	0.52	–
(7, 2)	225.23	0.27	m	189.57	0.06	–
(7, 3)	226.59	0.35	m	190.96	0.07	–
(6, 2)	228.84	0.64	1.6	194.09	0.16	–
(5, 2)	871.82	0.04	–	746.00	0.007	–
(4, 1)	1715.12	0.12	–	1390.69	0.02	–
(2, 1)	12 520.35	0.11	–	6917.54	0.11	–

Observed values are taken from Malinovsky and Heroux (1973).
m denotes that the line is masked.

In any case it seems to us that the lines corresponding to the transitions $^1P^0_1$-$^1D_2$ and $^3P^0_2$-$^3P_2$ should certainly be observable. Further, the Si VII line corresponding to the transition $^1P^0_1$-$^1D_2$ should be sufficiently intense for observation. We notice from Table II that the calculated flux for the S IX line at 223.27 Å is an order of magnitude less than that quoted by Malinovsky and Heroux (1973). We suspect that this line is blended.

We have also studied the variation in line emission per unit volume with height in the model atmosphere of Elzner (1976). The contribution of the various atmospheric layers to the total flux has been investigated. We find that, except for Ar XI lines, the emission comes mainly from a narrow region having an effectively uniform electron density and temperature.

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