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DIAGNOSTICS OF SOLAR PLASMA USING EMISSION LINES

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Abstract

The spectroscopic techniques in the X and EUV region to determine electron density and temperature of solar plasma have been presented The line intensity ratios as a diagnostic probe of solar plasma from berryllium, boron, nitrogen and oxygen - like ions have been discussed with a detailed investigation of carbon-like ions Absolute line fluxes from these ions at earth distance have also been discussed

1 Introduction

A high temperature plasma is vividly described by the famous astrophysicist Sir Arthur Stanley Eddington as follows

"Crowded together within a cubic centimeter there are more than a (trillion trillion) atoms, about twice as many free electrons, and (20 billion trillion) X rays The X rays are travelling with the speed of light and the electrons at 10,000 miles a second Most of the atoms are simply protons (i e hydrogen nuclei travelling at 300 miles a second) Here and there will be heavier atoms, such as iron, lumbering along at 40 miles a second I have told you the speeds and the state of congestion of the road, and I will leave you to imagine the collisions'

The X and EUV spectra of astrophysical objects have become available only since advent of space research X and EUV spectrometers and spectrographs of increasing sophistication have been flown on rockets, unmanned and manned spacecrafts These instruments have provided bewildering large amount of data which have opened up exciting new area in astrophysics Interpretation of these observations required atomic data for spectral transitions at X and EUV wavelengths of highly ionized atoms leading to new areas of research in atomic physics The process of identifying emission lines in the solar X and EUV spectrum has progressed through a combination of theoretical atomic physics, the production of similar spectra in laboratory experiments and understanding of the likely physical conditions in the solar atmosphere Even the early work of Grotrian (1931) and Edlen (1942, 1945) On the identification of magnetic dipole transitions in highly ionized iron observed in the visible spectrum of the solar corona during eclipses is an example of this fruitful combination of techniques The existence of these ions in the coronal gas led to the discovery of million degree hot corona The method of classifying lines from high stages of ionization by building up data from different elements along isoelectronic sequence has been widely used A variety of laboratory sources is available for producing the different states of ionization, for example, θ pinch devices, a range of spark sources of laser produced plasmas

High spatial and spectral resolution can be used to determine the physical conditions in high temperature plasmas The electron density and temperature can be derived from the intensity ratios of certain spectral lines The combined ion temperature and non thermal turbulence can be determined from spectral line profiles In some cases, the lines are primarily broadened by the Zeeman or Stark effect, and the analysis of the line shapes and widths allows the strength of the magnetic field or the electron density to be inferred The Doppler shifts of the lines reveal anisotropic mass motion The absolute intensity of certain emission lines and the knowledge of the emitting volume can be used to determine the abundance of impurity elements Each of these measurements involves isolating particular emission lines that are primarily sensitive to a single physical parameter These lines may fall in the X , the EUV the UV or even in the visible region of spectrum

In the section 2, theory of line formation is presented The electron temperature and density dependence of line intensity ratios have been discussed in the sections 3 and 4 respectively Section 5 deals with the solar atmosphere and line intensity ratios to diagnose solar plasma Closing remarks have been made in section 6

2 Theory of Spectral line formation

We consider a low density plasma where the number density N of different ion species is determined by electron impact ionization and radiative and dielectronic recombinations The ion number densities for an element with nuclear charge Z are determined by the set of coupled rate equations

$$\frac{\partial N_Z}{dt} + U \nabla N_Z = N_e(N_{Z-1}Q_{Z-1} + N_{Z+1}\alpha_{Z+1}) - N_eN_Z(Q_Z + \alpha_Z) \tag{1}$$

with the additional condition $\sum_0^Z N_Z = N$

where Q and α are ionization and recombination rate coefficients ($cm^3 sec^{-1}$), Z is the ionic charge N_e the electron density, N the number density of the element and U the plasma fluid velocity The solutions of eqn (1) are obviously model dependent for any realistic calculation The ionization equilibrium is generally valid or at least assumed and eqn (1) then becomes

$$N_Z Q_Z = N_{Z+1} \alpha_{Z+1} \tag{2}$$

The line emission from a given volume element is given by

$$\begin{aligned} E(j,i) &= \frac{1}{4\pi} A_{ji}\, h\, \nu_{ij} N_j \ (ergs\ cm^{-3} sec^{-1} sr^{-1}) \\ &= \frac{1}{4\pi} A_{ji} E_{ij} N_j \end{aligned} \tag{3}$$

The flux F_{ij} at earth in an optically thin spectral line is given by

$$F_{ij} = \frac{E_{ij}}{4\pi R^2} A_{ji} \int_{\Delta V} N_j \, dV \ (erg\ cm^{-2} sec^{-1}) \tag{4}$$

where E_{ij} is the energy of the transition between upper level j and lower level i, A_{ji} is the radiative transition probability ΔV is the volume of the plasma where the line is formed R is the earth to object distance, and N_j is the number density of the ions in excited level j The excitation processes are usually much faster than ionization and recombination time scales, particularly near ionization equilibrium The excitation can, therefore be decoupled from ionization and recombination That is, in many cases, excitation processes are dominant over ionization and recombination processes in producing an excited state In such cases, N_j can be found using detailed balance between excitation and radiative processes alone neglecting ionization and recombination processes The result is

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

$$\text{with} \quad \sum_j N_j = N_Z \qquad (5)$$

where N_e is the electron density C_{ij} the collision rate and R_{ij} are the photo excitation rates The collision rates ($cm^3 sec^{-1}$) are expressed in terms of the collision strengths Ω_{ij} in the form

$$C_{ij} = 8.63 \times 10^{6} \frac{\Omega_{ij}}{\omega_i T_e^{\frac{1}{2}}} \exp\left(\frac{E_{ij}}{K T_e} \right)$$

$$= 1.70 \times 10^{3} \frac{g f_{ij}}{T_e^{\frac{1}{2}} E_{ij}(eV)} \exp\left(\frac{E_{ij}}{K T_e} \right) \quad \text{(for excitations)} \qquad (6a)$$

$$C_{kj} = C_{jk} \left(\frac{\omega_j}{\omega_k} \right) \exp\left(\frac{E_{kj}}{K T_e} \right) \quad \text{(for de excitations)} \qquad (6b)$$

where T_e is the electron temperature K the Boltzmann constant E_{kj} the excitation energy and ω_i the statistical weight

$$N_j = \frac{N_j}{N_{ion}} (N_e, T_e) \frac{N_{ion}}{N_{el}} (T_e) \frac{N_{el}}{N_H} N_H$$

where in the simplest case $[N_j/N_{ion}] \sim 1.0$, $[N_{ion}/N_{el}]$ is the ionization equilibrium population for the ion and $[N_{el}/N_H]$ is the abundance of the element relative to hydrogen $N_H = 0.8 N_e$

3 Electron Temperature Measurements

There are two methods for determining electron temperature The more commonly known method involve using the Boltzmann factors in excitation rate coefficients If we consider an isothermal plasma of density N_e and volume V, the line intensity ratio of two lines from an ion, originating from excited levels k and j and terminating on lower level i is given by

$$\frac{E(j,i)}{E(k,i)} = \frac{E_{ij}}{E_{ik}} \frac{C_{ij}}{C_{ik}}$$

assuming for simplicity that levels k and j decay to only level i ($N_e C_{kj} << A_{kj}$) Using equation (6)

$$\frac{E(j,k)}{E(k,i)} = \frac{E_{ij}}{E_{ik}} \frac{\Omega_{ij}}{\Omega_{ik}} \exp\left(\frac{E_{ik} - E_{ij}}{KT} \right)$$

The intensity ratio in this equation is temperature sensitive if $(E_{ij} - E_{ik})/KT >> 1$ The method is independent of ionization equilibrium but does depend on the atmospheric structure We assume an isothermal plasma of constant density in deriving this equation Most real plasmas are not isothermal and density may vary with temperature In such a case, the excitation ratio coefficients cannot be removed from the integral equation and the intensity ratio depends on atmospheric structure in addition to temperature

Another method of determining temperature is simply to assume ionization equilibrium (Gabriel and Jordan 1975) There are many highly ionized atoms that are formed in ionization equilibrium over a very narrow temperature range (Jordan, 1969) This is true for most of the ions formed in the transition region between about 2 x 10^4K and 10^6K It is not true for most Li like, He like and H like ions which are formed over very broad temperature ranges (Jordan, 1970) However, if a line of an ion, such as C III or O III, is observed and ionization equilibrium is assumed, then from the equilibrium calculations, the temperature is known (i e $T_e \approx 6 \times 10'$ K for these ions)

Finally, an elegant method for determining temperature in high temperature low density plasmas has been developed by Gabriel and Jordan (Gabrial and Jordan 1972, Bhalla et al 1975) and independently by Vainstein and Safronova (1978) This method uses the temperature dependence of dielectronic recombination and electron impact excitation A line formed by only dielectronic recombination and a line formed primarily by electron impact excitation are chosen as shown in Fig 1, the Li like ion dielectronic X ray line and the He like ion resonance line The intensity ratio of these two lines can be quite temperature sensitive and this diagnostic is very useful for flare plasmas

4. Electron Density Measurements

Line ratios can be found that are sensitive primarily to electron density If the temperature of formation of the lines is also known, then the local electron pressure (N_eT_e) of the plasma can be calculated If the density sensitive line pairs can be found over a range of temperatures, then the pressure throughout the plasma can in principle be determined and this result is important from the hydrodynamical standpoint

Density sensitivity arises because of the existence of metastable level The transition probabilities for magnetic dipole transitions, and transitions that involve a spin change (intercombination lines), are much less than similar electric dipole transition probabilities that do not involve a spin change (allowed transitions) In order to illustrate density diagnostics, let us consider a hypothetical three level atom (Figure 2) with ground level i and two excited levels j and k For the sake of discussion, let us consider only the transitions as indicated After solving the balance equations for the levels j and k, we get

$$\frac{N_j}{N_k} = \frac{C_{ij}}{C_{ik}} \frac{A_{ki}}{A_{ji}} [1 + N_e \frac{C_{kj}}{A_{ki}} (1 + \frac{C_{ik}}{C_{ij}})]$$

Therefore, the intensity ratio for the two lines can be expressed as

$$\frac{E(j,i)}{E(k,i)} = \frac{C_{ij}}{C_{ik}} [1 + N_e \frac{C_{kj}}{A_{ki}} (1 + \frac{C_{ik}}{C_{ij}})]$$

If the level k is metastable then A_{ki} will be much smaller than it would be for allowed one Thus this ratio becomes density dependent when N_e begins to approach the value [A_{ki}/C_{kj} that is $N_e C_{kj} \approx A_{ki}$ For very large N_e the ratio is usually impractically large to measure reliably

5 The Solar Atmosphere

The method for determining density is not new and has been used by astronomers working in the optical spectral region for some time (Aller et al, 1949) The familiar diagnostic for astronomers is the O II ratio,

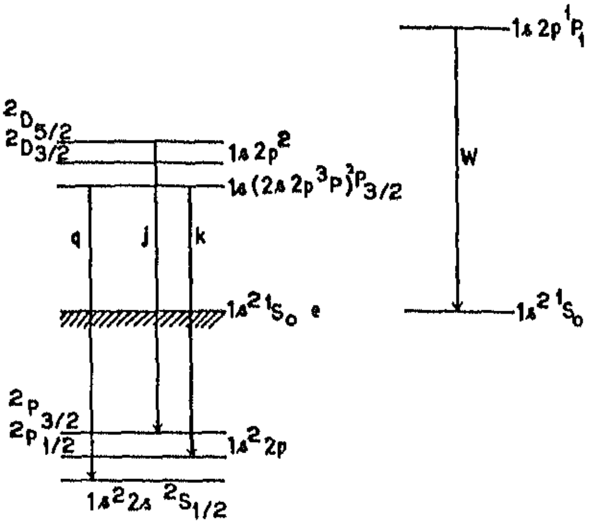

Fig 1 Energy level diagrams showing X ray lines formed by dielectronic recombination and collisional excitation

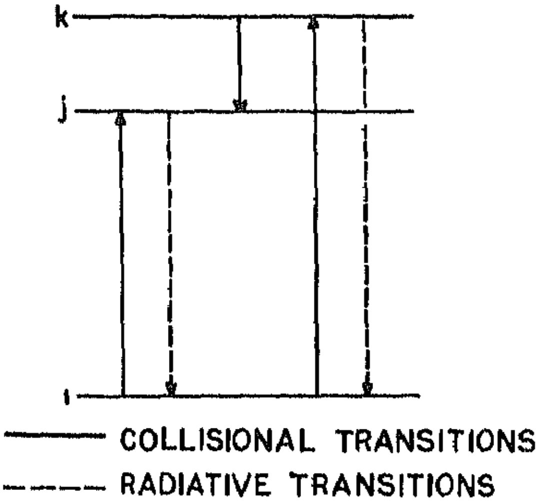

Fig.2 Schematic three level diagram for density diagnostics

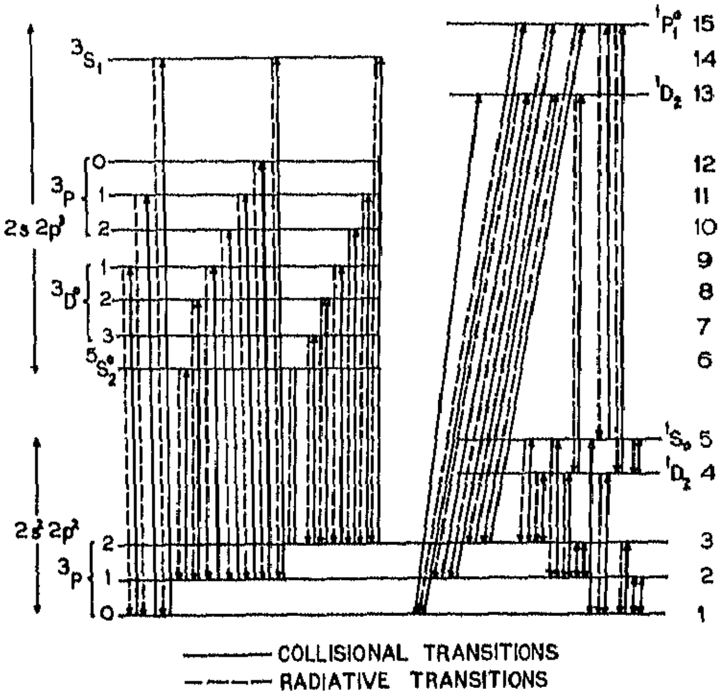

Fig 3 Energy level diagram for Cl like ions (Raju & Dwivedi, 1979)

$$\frac{2\,s^2\;2p^3\;(^4S_{\frac{3}{2}} \quad ^2D_{\frac{5}{2}})}{2\,s^2\;2p^3\;(^4S_{\frac{3}{2}} \quad ^2D_{\frac{3}{2}})}$$

that is, I (3730 Å)/I (3727 Å) This example from NI isoelectronic sequence, is similar to the three level case already discussed Both the upper levels $^2D_{3/2}$ and $^2D_{5/2}$ result in intercombination transitions to $^4S_{3/2}$ However, the lifetime of the $^2D_{5/2}$ level is significantly longer than the $^2D_{3/2}$ lifetime Therefore, within a limited range of densities, the $^2D_{3/2}$ level can be regarded as an allowed level relative to $^2D_{5/2}$ Density sensitivity for the O II ratio occurs around 10^3 cm^{-3} (Osterbrock, 1975) The O II ratio is not a useful diagnostic for the solar atmosphere However, if more highly ionized ions in the N I sequence are considered, examples can be found that are useful at solar densities (Raju 1978, Feldman et al, 1978) Forbidden lines of the ions Mg VI, Si VIII, S X and Ar XII can be used to determine electron densities in the inner corona The same line ratio considered for O II is an excellent diagnostic at coronal densities for these heavier ions particularly S X

The C III seems to be the first ion considered for application to the solar transition region (Jordan 1971, Munro et al 1971) Ions in the Be I isoelectronic sequence have rich emission line spectra in the solar X and EUV region (Gabriel and Jordan 1972) Observations of the relative strengths of these lines in a given ion have been widely used to probe the solar and astrophysical plasma (Jordan 1974, Malinovsky 1975) Loulergue and Nussbaumer 1976, Doschek et al 1977, Dufton et al 1978, Dufton et al 1983 Keenan et al 1984) Lines emitted from born like ions have also received considerable attention to probe the solar atmosphere (Elwert and Raju, 1975, Flower and Nussbaumer 1975a,b; Vernazza and Mason 1978, Dwivedi and Raju 1980 and others)

Although Mason (1975) has reported calculations for Ca XIII ion, the first detailed investigations on some lower ions in the OI isoelectronic sequence were reported by Raju and Dwivedi (1978) The density sensitivity of line intensity ratios of ions in the C I isoelectronic sequence has been studied in detail by Mason and Bhatia (1978) and independently by Raju and Dwivedi (1979) and we briefly discuss the same in the following

Figure 3 illustrates the energy level scheme adopted for carbon like ions The various physical processes considered are as indicated Here, the density determination becomes possible because of the first five levels which are metastable For electron densities in the relevant range, the collisional and radiative de excitation rates for these levels compete, therefore, the level population and consequently the line intensity ratios become density dependent Since the level population of higher term levels is essentially determined by the ground term levels, the variation of the population of these levels with electron density is reflected in the variation of line emission with electron density We have shown in Figures 4 and 5 the variation of ground state level populations as a function of electron density The temperature indicated in these figures correspond to maximum relative ion abundance of the elements We find that ground state level populations vary with electron density Therefore, the line intensities which are excited from the ground levels and emitted from different excited levels are expected to show density sensitivity

In Figures 6 and 7 we have shown line intensity ratios as a function of electron density for Ne V, Mg VII, Si IX and S XI These line intensity ratios are rather insensitive to temperature variation There are not many observed lines from these ions with calibrated intensities suitable for density determinations In order to check if 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 6 and 7 They fall on the density sensitive portions of the curves, thereby providing a direct method for determining N_e

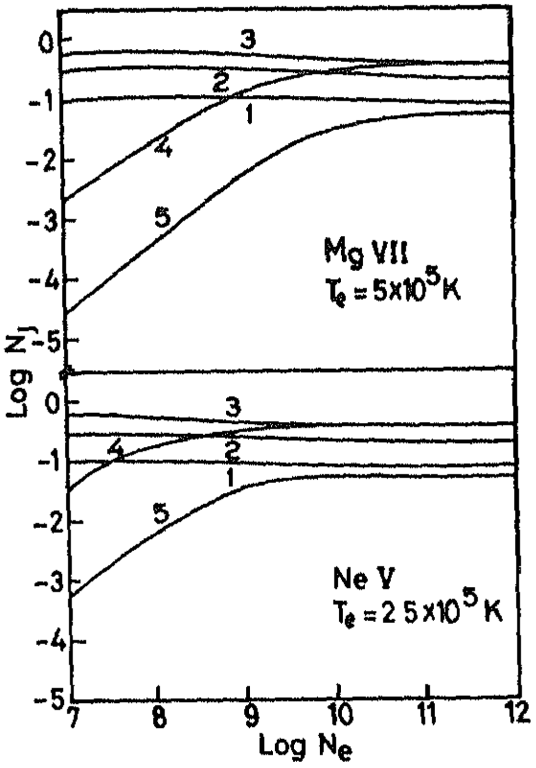

Fig 4. Log of ground state level population (N_j) as a function of log of N_e for Ne V and Mg VII T_e corresponds to the temperature for the maximum relative ion abundance of the element

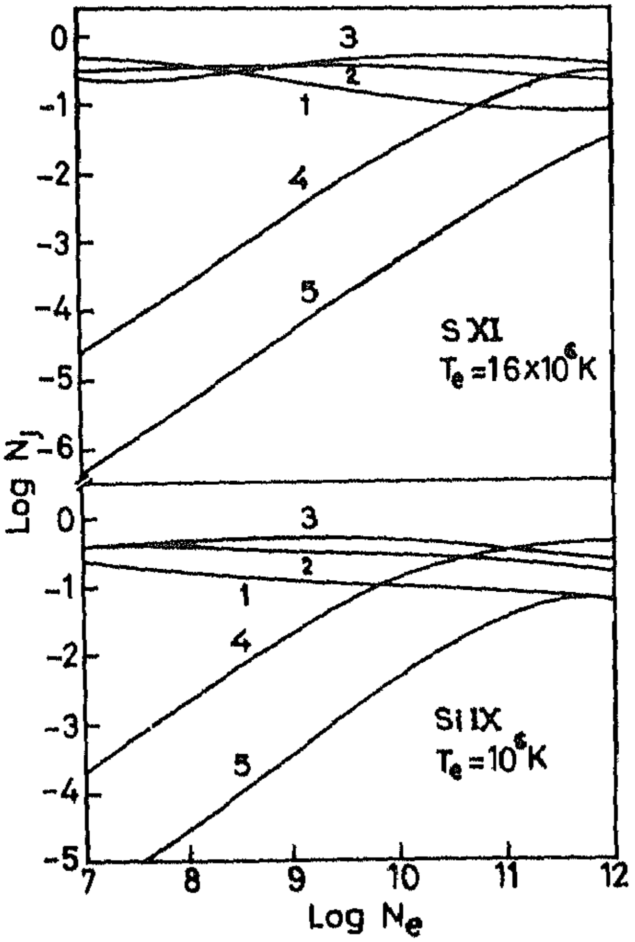

Fig.5 Log of ground state level population (N_j) as a function of log of N_e for Si IX and S XI T_e corresponds to the temperature for the maximum relative ion abundance of the element

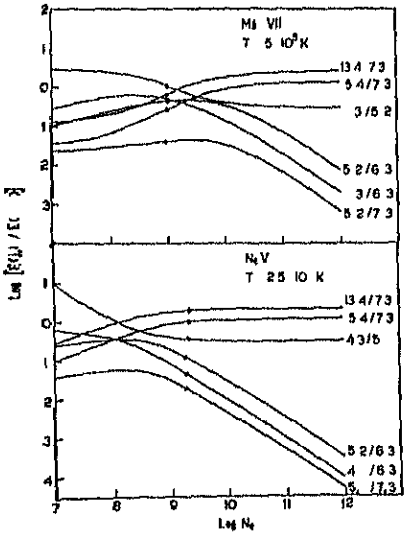

Fig.6. Log of intensity ratios E(j i)/E(n,m) of Ne V and Mg VII lines as a function of log of N_e Dots correspond to the calculated intensity ratios based on the model of Elzner (1976) T_e corresponds to the temperature for the maximum relative ion abundance of the elements (Raju and Dwivedi, 1979)

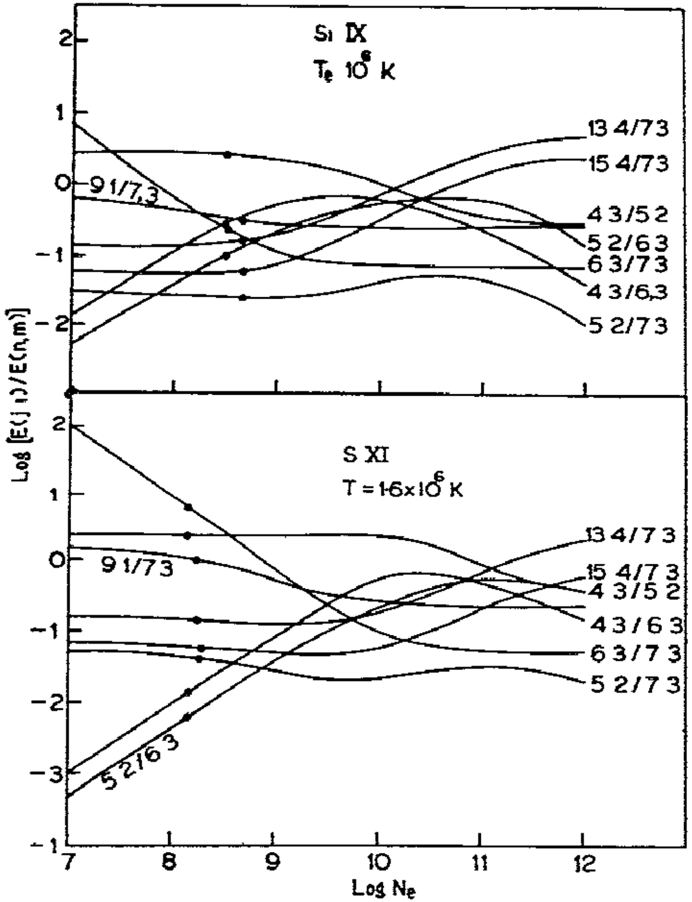

Fig.7 Log of intensity ratios E(j i)/E(n m) of Si IX and S XI lines as a function of log of N_e Dots correspond to the calculated intensity ratios based on the model of Elzner (1976) T_e corresponds to the temperature for the maximum relative ion abundance of the elements (Raju and Dwivedi 1979)

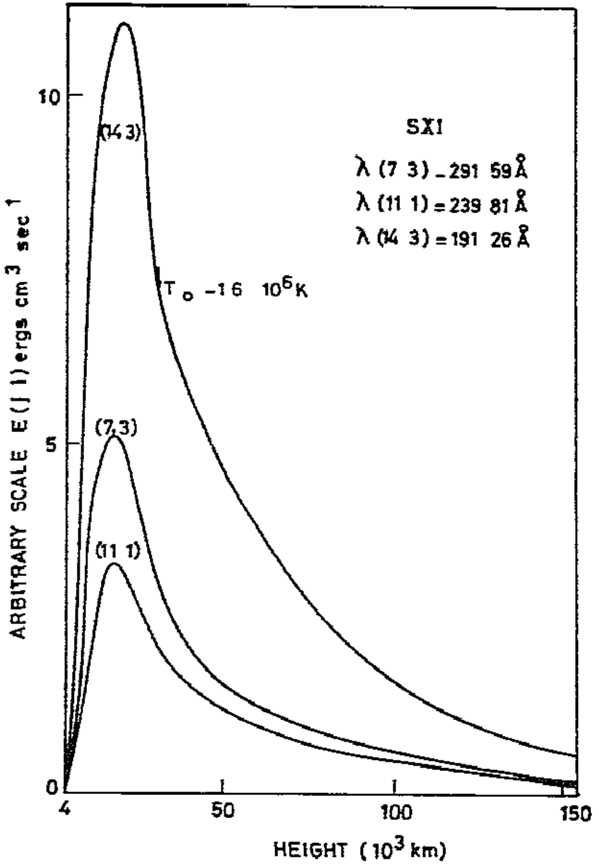

Fig.8. Emission for unit volume [in the units of (N_{el}/N_H) X arbitrary scale factor] against height in the model atmosphere of Elzner (1976) for S XI lines

From Figures 6 and 7 we notice that the forbidden lines with transitions $^1S_0$ $^3P_1$ and $^1D_2$ $^3P_2$ relative to the intersystem line $^5S^0_2$ $^3P_2$ are density sensitive, particularly suitable for active regions. Forbidden line $^1S_0$ $^3P_1$ relative to the allowed line $^3D^0_3$ $^3P_2$ could also be used as a density indicator for active regions. The intensity ratios of forbidden lines corresponding to transitions $^1D_2$ $^3P_2$ and $^1S_0$ $^3P_1$ for the ions Mg VII, Si IX and S XI could also be useful for active region conditions. Sandlin et al (1977) have observed in two active regions off the limb, lines corresponding to the intersystem transitions $^5S^0_2$ $^3P_1$ and $^5S^0_2$ $^3P_2$ as well as forbidden transition $^1S_0$ $^3P_2$ of Ne V. In the case of Mg VII, they observe the forbidden line with transition $^1S_0$ $^3P_2$. However, two forbidden lines corresponding to the transitions $^1D_2$ $^3P_1$ and $^1D_2$ $^3P_2$ are observed for Si IX and S 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 0.05 for Ne V line at 1574.82 Å and 1.9 for Mg VII line at 1189.92 Å for the acltive region AR 12300 at 40" above the limb, 2.5 for Mg VII for 1189.82 Å and 6.6 and 11 for Si IX at 1984.88 Å and 2149.26 Å respectively whereas 0.4 and 2.8 for S XI at 1614.51 Å and 1826.21 Å for the active region AR 12114 at 4 arc sec above the limb. The Ne V and Mg VII lines correspond to the transition $^1S_0$ $^3P_1$ whereas Si IX and S XI lines correspond to the transitions $^1D_2$ $^3P_1$ and $^1D_2$ $^3P_2$ respectively. Sandlin et al (1977) have quoted the conversion factor to get absolute intensity only in the case of active region 4 arc sec off the limb. In view of the intensity ratios discussed above, lines corresponding to the transition $^5S^0_2$ $^3P_2$ of Mg VII, Si IX and S XI must definitely be observable in active regions.

We have calculated line fluxes from the entire solar disk at earth's distance for various strong and weak lines of Ne V, Mg VII, Si IX and S XI of carbon sequence. However we list in Table 1 the result of S XI lines for the sake of brevity. Calculated fluxes for these lines may be useful in resolving difficulties associated with line identification, masking or blending due to lines arising from the ions of other isoelectronic sequences. The line emission per unit volume against height in the model atmosphere of Elzner (1976) for some of the intense lines of S XI have been shown in Fig 8. This diagram indicates the contribution of various atmospheric layers to the total flux. From Figures 6 and 7, we see that the line intensity ratio with transitions $^1D^0_2$ $^1D_2$ and $^1P^0_1$ $^1D_2$ relative to the strongest line corresponding to the transition $^3D^0_3$ $^3P_2$ for Ne V and Mg VII could be used as density indicator for quiet sun regions. Our model calculations help us make the definite conclusion that singlet to singlet lines of Ne V and Mg VII are intense enough for observation. Further the line intensity ratios of singlet to singlet relative to triplet to triplet transitions are useful probes for the quiet sun. In the case of Si IX and S XI, this ratio could be useful for active regions. Calculated flux values for S XI lines in the range 190 Å 285 Å have greater discrepancy over observed ones. This could partly be ascribed to blending of those lines.

We have discussed the carbon sequence in some detail. A similar study of oxygen, nitrogen and boron sequences has been carried out. The lines emitted in the X and EUV region have been used as a density monitor of the solar plasma. Using a model by Kopp and Orral (1976), line intensities from the quiet sun and coronal hole have also been estimated (Dwivedi and Raju 1985) which is useful in identifying close lines arising from different ions prevalent in the atmosphere. Such a study provides first hand information to predict lines which have hitherto not been observed for future observation. Moreover, this study could also act as a test or constraint on the model atmosphere when compared with observational data. In our opinion this kind of study might also help avoid wrong interpretation of the observational data by adjusting atomic parameters in order to match the observations (Vernazza and Mason, 1978). However, we need more observations with better spectral resolution than currently available to substantiate our contention (Dwivedi and Raju, 1980). For a review of solar observations of the n = 2 2 transitions in fourth period elements, the reader is referred to an article by Lawson and Peacock (1984).

Table 1

Calculated Fluxes from the entire Solar Disk at Earth s distance
(Raju and Dwivedi, 1979)
S XI ion, n(S)/n(H) = 1 99 x 10^{5}

Transition	λ(Å)	Flux (10^{3} ergs cm^{2} sec^{1}	
		Calculated	Observec
(14, 1)	186 85	0 33	
(14, 2)	188 68^b	0 95	1 6*
(14, 3)	191 26	1 39	2 3*
(15, 4)	190 37	0 03	
(13, 4)	215 95	0 08	
(11, 1)	239 81	0 39	1 4*
(10, 3)	246 90^b	0 38	1 5*
(11, 3)	247 12^b	0 43	1 6*
(9, 1)	281 40	0 56	2 3*
(9, 2)	285 58^b	0 51	1 4*
(8, 2)	285 83^b	0 48	1 6*
(7, 3)	291 59	0 57	0 85*
(6, 2)	555 00	1 68	
(6 3)	578 00	3 68	
(5, 2)	782 76	0 02	
(4, 2)	1614 51**	0 03	
(4, 3)	1826 21**	0 05	

* Observed values from Malinovsky and Heroux (1973)
** Observed lines in active regions from Sandlin et al (1977)
b denotes that the line is blended

6. Closing Remarks

This review gives some idea of the power of spectroscopy to uncover secrets governing the behaviour of high temperature plasmas The technical know how and the basic theory underlying the interpretation of the data, represent the harvest of the tremendous effort put forth to understand solar phenomena through space observations

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