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Departure from Maxwellian Velocity Distribution of High Temperature Plasma in Solar Flares where Almost All Electrons have been Stripped out from Iron Atoms

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Abstract

The spectral line intensity is proportional to the contribution function. The Contribution function can be found by taking product of fractional ion abundance and its excitation rate coefficient of upper state of transition emitting the spectral line in consideration. In present work the fractional abundance, excitation rate coefficient and Contribution function of Fe XXV (λ = 1.85 A^{o}) and Fe XXVI (λ = 1.79 A^{0}) as a function of Electron Temperature are computed and presented graphically. The contribution function of these ions is compared with their observed contribution function. The electron temperature for computed contribution function values are found slightly greater compared to values of the electron temperature corresponding to values of observed contribution function due to departure from maxwellian velocity distribution in a high temperature plasma in solar flares where almost all electrons of Iron have been stripped out.

Keywords: Solar flares, excitation Rate Coefficient, fractional Abundance, contribution function, Electron Temperature.

Subject Classification: Plasma

1. Introduction

It is well known that energy states of atoms and ions in the plasma are populated by electron collisions and depopulated by collisions of ions with slow electrons. Besides the collisional processes the atomic and ionic states are populated and depopulated due to some radiative processes also.

Electrons passing through the plasma transfer their energy to the plasma particles by two types of collisions i) Elastic collisions ii) Inelastic collisions.

In elastic collisions the transfer of kinetic energy of electron in to the kinetic energy of the plasma particles (atoms or ions) takes place. In this process the kinetic energy of the colliding particles is conserved. This type of collisional process is responsible to the heating of the plasma particles to some extent. In fact the second type of collision i.e. inelastic collisions are mainly responsible for the excitation of atoms and ions in the plasma. Any collision in which the internal energy of excitation of a particle is changed is referred to as inelastic collision. In this type of collision the kinetic energy of electron is converted into potential energy of colliding plasma particles and the plasma particles get excited. These particles in excited states either transfer their energy back to the electron or they undergo a transition giving radiative emission. The rate of transfer of energy from the electrons to the plasma particles may be written as,

$$\frac{dE}{dt} = N_g C_e N_e E_c + \sum_j N_{gi} N_e C_{in} E_j - \sum_j N_{gi} N_e C_{dex} E_i \tag{1}$$

where, N_g is number of gas particles. C_e is coefficient of elastic collision. E_c is energy transferred in elastic collisions. C_{in} is rate coefficient of inelastic collisions. E_j is energy of the j^{th} state excited by elastic collision. C_{dex} is de-excitation rate coefficient. E_i is energy of excited particles which transfers its energy to the electrons.

The sum runs over all possible energy states of the plasma particles.

2. Electron Impact Excitation (EIE)

In electron impact excitation, the energy from the high energy electrons is transferred to the colliding atoms or ions in the plasma. When an electron having energy more than the excitation energy of an electron rotating around nucleus of an atom / ion collides with the atom / ion may transfer its energy to the system and this may result in excitation of the rotating electron to a higher orbit. The probability of excitation depends upon energy of exciting electron and cross section of excitation at that particular energy. The excitation rate depends upon the excitation cross section and the number of effective collisions made by the electron. The number of effective collisions is function of electron velocity, which intern is a function of electron temperature (T_e). As we know that the plasmas consists of atoms, ions and electrons, there can be two types of electron impact excitation processes depending upon whether the colliding particles are atoms in ground state or ion in ground state. And accordingly these electron impact excitation (EIE) rate coefficients are defined as direct excitation and stepwise excitation respectively.

2.1 Penning Excitation

Excitation energy can be exchanged between neutral atoms. In particular, an excited atom can get ionized by virtue of its excitation energy, if the later is larger than the required ionization energy. Such a process is made more probable if the excited atom is in metastable state and has thus longer lifetime in which the particle may undergo an effective collision. When one of the colliding atoms is in metastable state and the other one is in ground state, there is a probability of ionizing second atom and getting excited to the excited state depending upon the energy of the metastable atom. Such a process is referred to as penning excitation.

2.2 Duffenduck Excitation

The process in which an ion having charge z in a ground state, when collide with the other ion having charge z' in ground state, transfers its energy to the colliding partner and the other ion gets ionized. This process of ionization and excitation of one ion and recombination of other ion is known as duffenduck excitation or charge transfer.

3. The Excitation Rate Coefficients

Excitation Rate Coefficients are useful in computing the contribution functions of various spectral lines. In present work, to study the excitation rate coefficient of different ionic species of iron, we have computed excitation rate coefficient of iron ions Fe XXV and Fe XXVI using formulae used in [1] as a function of electron temperature and few amongst them are presented graphically in figure (1).

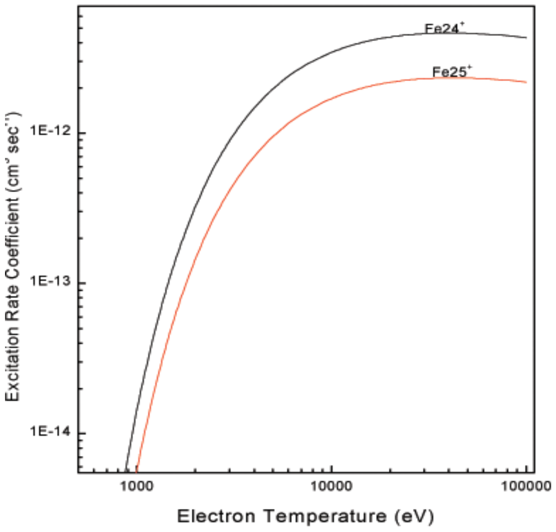

Fig. 1: *Excitation Rate Coefficient Of Fe XXV and Fe XXVI As A Function Of Electron Temperature.*

From all the graphs it observes that, the excitation rate coefficient (ERC) is very sensitive function of the electron temperature before it reaches its peak value but the variation of the function becomes very slow varying function of electron temperature near its saturation value.

4. Fractional Abundance

Plasma consists of the electrons and the ions with different charges. The collision between the atoms, ions of different charges and electrons results in ionization. At the same time the ions may capture the electrons and results in formation of ions of lower charge. The ionization and Recombination processes compete each other so that the ionization rate and recombination rate reach, each to a certain value and equilibrium is attained. As long as the electron temperature is not changed the equilibrium remains in a particular state. A change in electron temperature results in changing the densities of ions and electrons. Thus densities of ions and electrons are completely dictated by the electron temperature. The plasma emission depends upon the fraction of total density of species remaining in a particular ionized state, the electron density and the electron temperature.

The amount of the fraction of the total density of species remaining in a particular ionized state is called as fractional abundance of that ion.

Equation for the time rate of change of population density of ion of charge z can be written as,

$$\frac{dN_z}{dt} = n_e\left\{-N_z S_z + N_{z-1}\, S_{z-1} - N_z\, \alpha_z + N_{z+1}\, \alpha_{z+1}\right\} \qquad (2)$$

where z takes all values between 0 and maximum charge on the ion.

The ionization state of each element of atomic number z is controlled by electron impact ionization (including autoionization) from state z → z +1 with total rate coefficient $S_{z,z}$ (cm^3 sec^{-1}) and radiative plus dielectronic recombination z+1→ z with rate coefficient $S_{z,z+1}$ (cm^3 sec^{-1})

In steady state, the time rate of change of population density of ion of charge z will be zero.

In steady state condition, where the time rate change of population density of ion of charge z will be zero, the equation (14) reduces to,

$$N_z \;\; S_z = N_{z+1} \;\; \alpha_{z+1} \qquad (3)$$

The population density ratio ($N_{z,z+1}/N_{z,z}$) of two adjacent ion stages $Z^{+(z+1)}$ and Z^{+z} can be derived by using steady state equation (3).

$$\frac{N_{z+1}}{N_z} = \frac{S_z}{\alpha_{z+1}} \tag{4}$$

where $S_{(z)}$ is ionization rate coefficient of ion of charge z. α_{z+1} is recombination rate coefficient of ion of charge z+1. N_Z and N_{Z+1} are densities of ion with charge z and z+1 respectively.

4.1 Expression for Fractional Abundance

Population density ratio ($N_{Z,\ z+1}$ / $N_{Z,Z}$) can be evaluated in terms of S_Z and α_{z+1}, as the values of S_Z and α_{Z+1} are fully determined by the electron temperature. Therefore the fractional abundance and population density of any ion in the plasma depends only on the electron temperature. The equation for fractional abundance of a Fe XXV and Fe XXVI species in plasma is written by using equation (4) and the procedure followed by [2].

The fractional abundance of an ion of charge z can be written as,

$$F_z = \frac{N_z}{\sum_{z'} N_{z'}} \tag{5}$$

where F_z is the fractional abundance of ion of charge z. and N_z is the density of ion with charge z. The sum runs over all possible ionized states.

To study the behaviour of Fractional abundance of Fe XXIII through Fe XXVI as a function of electron temperature, they are computed using equation (5) and are presented graphically in figure (2).

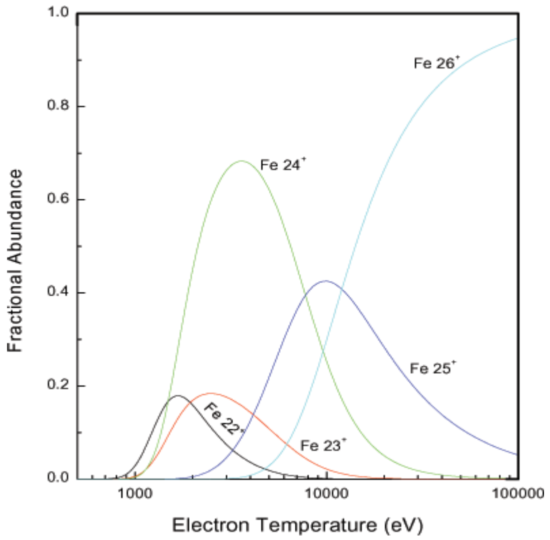

Fig. 2: Fractional Abundance Of Iron Ions As A Function Of Electron Temperature.

5. The Contribution Function

The contribution function is an electron temperature dependent part of the flux emitted by a spectral line and it is a measure of spectral line intensity because, spectral line intensity is proportional to their contribution function. The contribution function can be defined as the product of fractional ion abundance and the excitation rate coefficient of the upper state of the transition emitting the spectral line in consideration [3]. The equation for contribution function can be written as,

$$C(z) = N_z \; R_{zu} \qquad (6)$$

Where N_z is the fractional density of the ion of charge z and R_{zu} is the electron impact excitation rate coefficient of the state u of ion of charge z.

6. The Results and Discussion

The Contribution Function Of Fe XXV (λ = 1.85 A°) as a function of electron temperature is computed and presented graphically in figure 3. The normalized curve of contribution function of Fe XXV (dotted curve) is compared with observed contribution function (solid curve) of it in figure (4). Both curves are in close agreement with each other. The electron temperature at which solid curve and dash dot curve reaches to peak is 5.909 **x** 10^7 °K and 6.383 **x** 10^7 °K respectively. But at such a very high electron temperature, all the electrons in the plasma may not have maxwellian velocity distribution. Some electrons may have non-maxwellian velocity distribution. By assuming 10% of electrons have non-maxwellian velocity destribution and 90% electron have maxwellian velocity destribution, the contribution fucntion is computed and plotted as a function of electron temperature (dash dot curve) and is compared with observed contribution function (solid curve) in figure(5). If we observe these curves, it observe that, both curves shows very good agreement. The electron temperature at which solid curve and dash dot curve shows peak are 5.91**x**10^7 °K and 5.90 **x** 10^7 °K.

Thus we can conclude that, in a plasma at high electron temperature where almost 24 electrons have been stripped out from iron, neither the electrons have maxwellian velocity distribution nor they have non-maxwellian velocity distribution, but the electrons have mixed velocity distribution. Figure (6) shows the computed contribution function of Fe XXV (λ = 1.85 A⁰) as a function of electron temperature.

We have also compared the computed normalized curve of contribution function of Fe XXVI (λ = 1.79 A⁰) (dash dot curve) assuming all the electrons having maxwellian velocity distribution with its observed contribution function (solid curve) in figure (7).

In figure (7), the electron temperature at which the solid curve and the dash dot curve shows peaks are 120.5 x 10^6 °K and 136.4 x 10^6 °K respectively. By assuming 10 % of electrons having non-maxwellian velocity distribution and 90 % of electron having maxwellian velocity distribution, we have computed contribution function for Fe XXVI (λ = 1.79 A⁰) and is plotted in figure (8) as a function of electron temperature (dash dot curve), along with observed contribution function. Both curves shows close agreement with each other up to peak and have slight error after peak.

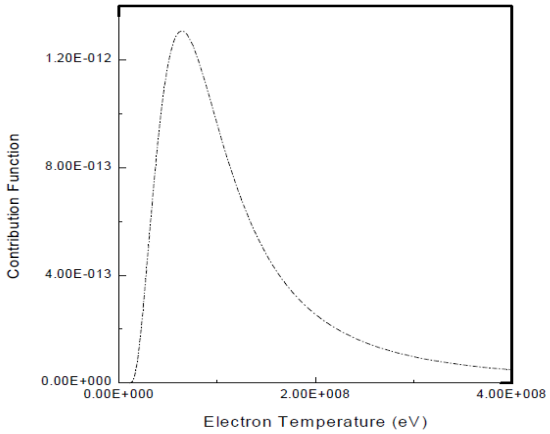

Fig. 3 : Contribution Function (Without Normalization) Of Fe XXV (λ = 1.85 A^{o}) As a Function of Electron Temperature.

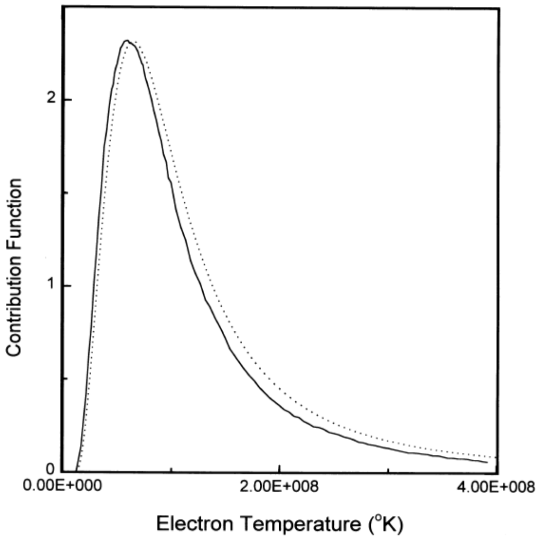

Fig. 4 : Normalized Curve (Dotted Curve) For Contribution Function Of Fe XXV (λ = 1.85 A^{o}) In Present Work Is Compared With Observed Contribution Function (Solid Curve) As A Function Of Electron Temperature.

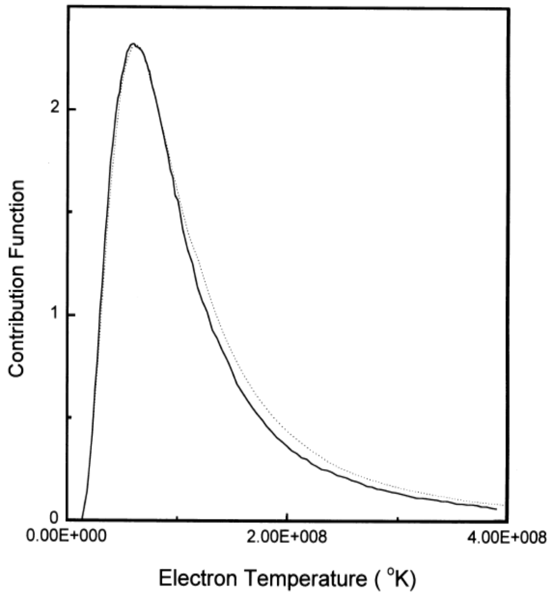

Fig. 5: Normalized Curve (Dash Dot Curve) For Contribution Function Of Fe XXV (λ = 1 .8 5 A^0) With Mixed Maxwellian Velocity distribution In Present Work Is Compared With Observed Contribution Function (Solid Curve) As A Function Of Electron Temperature.

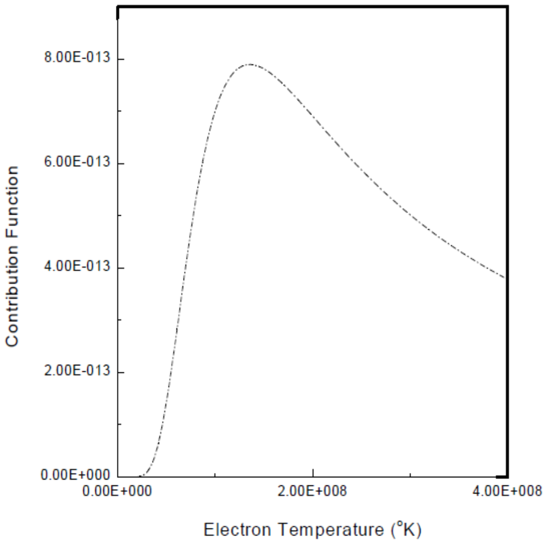

Fig. 6: Contribution Function Of Fe XXVI (λ = 1.79 A^0) (Without Normalization) As A Function Of Electron Temperature.

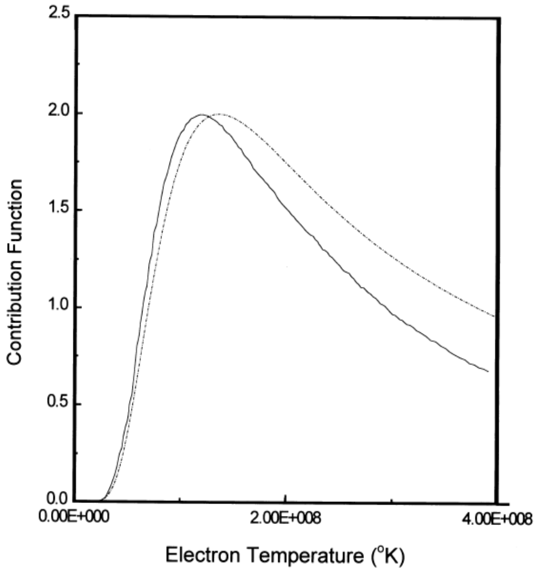

Fig. 7 : Normalized Curve (Dotted Curve) For Contribution Function of Fe XXVI (λ = 1.79 A°) In Present Work Is Compared With Observed Contribution Function (Solid Curve) As A Function Of Electron Temperature.

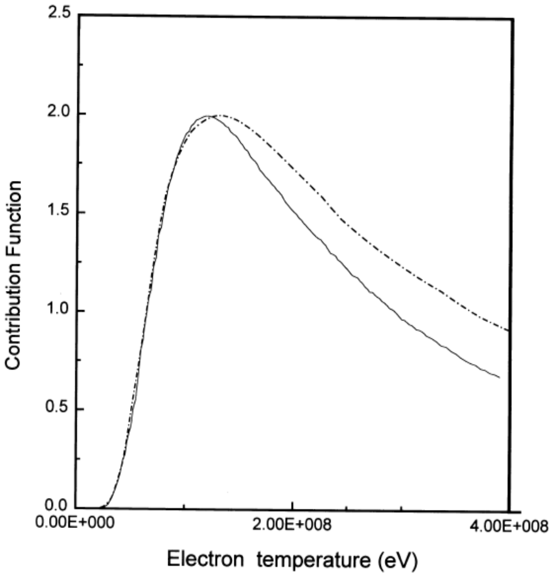

Fig. 8: Normalized Curve (Dash Dot Curve) For Contribution function of Fe XXVI (λ = 1.79 A^0) With Mixed Maxwellian Velocity distribution In Present Work Is Compared With Observed Contribution Function (Solid Curve) As A Function Of Electron Temperature.

7. Conclusion

Plasma at high electron temperature where almost all electrons have been stripped out from iron, neither the electrons have maxwellian velocity distribution nor they have non-maxwellian velocity distribution, but the electrons have mixed velocity distribution.

8. References

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