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Effect of dielectronic recombination excitation in the solar x-ray lines of calcium-ions

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Abstract. The effect of dielectronic recombination as an excitation process in the intensity of solar x-ray lines of calcium ions is investigated. It is found that x-ray line intensities are enhanced by 15% to 88% with the inclusion of dielectronic recombination as an excitation mechanism.

Keywords. Solar lines; line intensities; dielectronic recombination.

1. Introduction

Pioneering work on dielectronic recombination (dr) was carried out by Burgess (1964) in the ionisation equilibrium of low density and high temperature plasma. Later on he approximated it into a simplified formula (Burgess 1965) which has been used by a number of workers (Van Rensbergen 1967; Ansari *et al* 1970; Chandra 1978).

Mewe (1972) calculated the intensities of a number of x-ray lines, emitted from solar atmosphere, as a function of temperature by considering the electron impact excitation followed by radiative emission. However, these results cannot be relied upon because the excitation due to dr which plays a key role in the x-ray region, was not taken into account. Ansari and Alam (1975) considered the excitation due to dr also and calculated the average line intensities and line intensities as a function of temperature for Si ions. They adopted the formula for dielectronic recombination excitation proposed by Gabriel (1972) for He-like ions. Further the method of Ansari and Alam (1975) for inclusion of dr is erroneous as they assumed that the dielectronic recombination excitation rates also depend on the density of the ion from which the line is emitted.

In this paper, the average line intensities of the x-ray lines emitted from solar atmosphere from calcium ions are investigated by considering the excitation due to dr along with the electron impact excitation followed by radiative decay. In order to determine the contribution of dielectronic recombination excitation the calculations have been repeated by excluding the excitation due to dr.

2. Theory

Following Pottasch (1963) the intensity of the line (in erg cm^{-2} s^{-1}) observed at the earth's distance is given by (Chandra 1978)

$$I = 1{\cdot}744 \times 10^{-17}\, W_{ij} \int N_j^m A_{ji}\, dh. \qquad (1)$$

The integration is performed over the line forming region. Here W_{ij} (eV) is the energy difference between the corresponding levels, A_{ji} (s^{-1}) the spontaneous transition probability and N_j^m is the population density of the ion under consideration in the state j which can be obtained with the help of the equation

$$N_j^m \sum_{k<j} A_{jk} = N_e N_g^m C_{gj} + N_e N_g^{m+1} C_{gjd}. \tag{2}$$

g is used for the ground state (i may or may not be the ground state). Here the collisional de-excitation rates, which are quite negligible as compared to A_{jk}, and the photo-excitation rate coefficients, which are negligible as compared to C_{gj} and C_{gjd}, are not considered. C_{gj} is the electron impact excitation rate coefficient for the process:

$$\mathrm{Ca}^{+m}(g) + e \rightarrow \mathrm{Ca}^{+m}(j) + e, \tag{3}$$

and C_{gjd} is the dielectronic recombination excitation rate coefficient for the process:

$$\mathrm{Ca}^{+m+1}(g) + e \rightarrow \mathrm{Ca}^{+m}(j, j'). \tag{4}$$

The electron in the state j of the Ca^{+m} ion de-excites through the process:

$$\mathrm{Ca}^{+m}(j) \rightarrow \mathrm{Ca}^{+m}(i) + W_{ij}. \tag{5}$$

or

$$\mathrm{Ca}^{+m}(j, j') \rightarrow \mathrm{Ca}^{+m}(i, j') + W_{ij}. \tag{6}$$

A well known formula for C_{gj} proposed by Van Regemorter (1962) (with gaunt factor $g = 0{\cdot}2$).

$$C_{gj} = 1{\cdot}7 \times 10^{-3}\, W_{gj}^{-1} T^{-1/2} f \bar{g} \exp\left(-W_{gj}/kT\right) \tag{7}$$

is used here. The coefficients for dielectronic recombination excitation viz C_{gjd} are calculated with the help of the formula of Burgess (1965) (Van Rensbergen 1967)

$$C_{gjd} = 8{\cdot}22 \times 10^{-4}\, T^{-3/2} f\, W_{gj}^{1/2} A(x)\, B(Z)$$

$$\exp\left[-1{\cdot}1613 \times 10^{4}\, W_{gj}\, T^{-1} \left(1 + \frac{0{\cdot}015 Z^{3}}{(Z+1)^{2}}\right)^{-1}\right], \tag{8}$$

$$A(x) = (1 + 0{\cdot}105\, x + 0{\cdot}015\, x^{2})^{-1}, \qquad x = W_{gj}/13{\cdot}6\,(Z+1),$$

$$B(Z) = Z^{1/2} (Z+1)^{2} (Z^{2} + 13{\cdot}4)^{-1/2}; \qquad Z = m + 1,$$

Z ($= m + 1$) is the charge of the recombining ion. Other symbols have their usual meanings.

On substituting the expression for N_j^m from equation (2) in equation (1) and rearranging, one gets

$$I = 1{\cdot}744 \times 10^{-17} \, W_{ij} \frac{A_{ji}}{\Sigma A_{jk}} \frac{N_E}{N_H} \frac{N_H}{N_e} \int G(T) \, N_e^2 \, dh, \tag{9}$$

where N_E/N_H is the elemental abundance relative to hydrogen which for calcium is taken as 6×10^{-6} (Mason 1975), $N_H = 0{\cdot}8 \, N_e$ and the function $G(T)$ is given by

$$G(T) = (N_g^m/N_E) \, [C_{gj} + (N_g^{m+1}/N_g^m) \, C_{gjd}]. \tag{10}$$

The ion abundances N_g/N_E are taken from Mewe (1972). Following the arguments made by Pottasch (1963) the function $G(T)$ may be taken out of the integral and should be substituted by $0{\cdot}7 \, G_{\max} \, (T_{\max})$, where $G_{\max} \, (T_{\max})$ is the maximum value of $G(T)$ at the line temperature $T_{\max}$. Again adopting the value of $\int N_e^2 \, dh$ $(=7 \times 10^{26}$ reported by Pottasch 1963) one obtains a simple expression for the average line intensity as

$$I = 6{\cdot}84 \times 10^{9} \, W_{ij} \, (N_E/N_H) \, (A_{ji}/\Sigma \, A_{jk}) \, G_{\max} \, (T_{\max}). \tag{11}$$

3. Results

The values of the oscillator strengths and $A_{ji}/\Sigma A_{jk}$ are taken from the tables of Mewe (1972). Energies W_{ij} are calculated with the help of wavelengths of the lines. $G_{\max} \, (T_{\max})$ are obtained graphically by plotting the graph of $G(T)$ versus tempera-

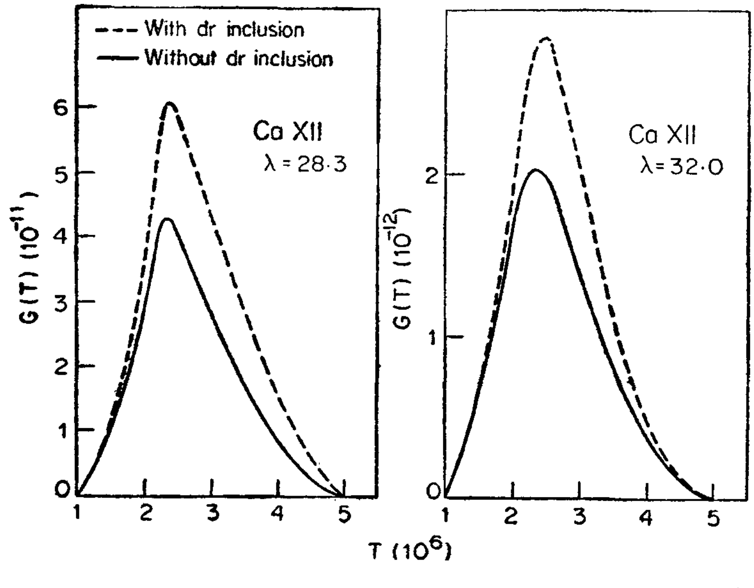

Figure 1. Variation of $G(T)$ versus T for Ca XII wavelengths 28·3 Å and 32·0 Å

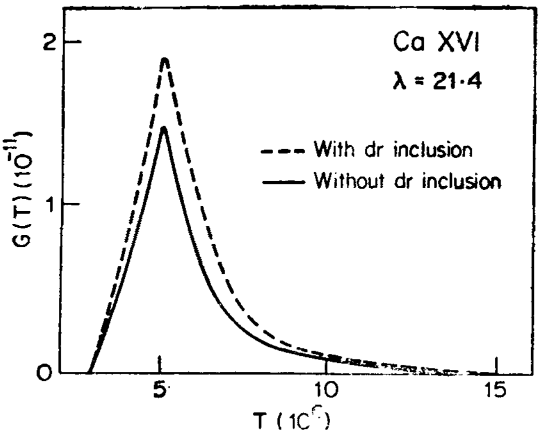

Figure 2. Variation of $G(T)$ versus T for Ca XVI wavelength 21·4Å.

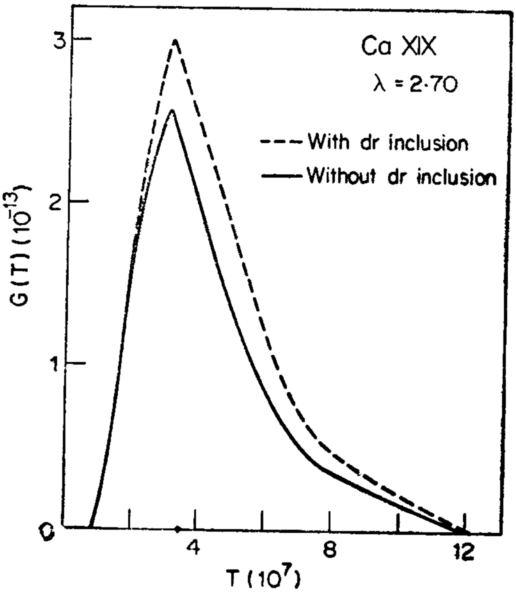

Figure 3. Variation of $G(T)$ versus T for Ca XIX wavelength 2·70Å.

ture T. Calculated line intensities are reported in table 1 along with the line temperature $T_{\max}$. In order to verify the argument of Pottasch the graphs of $G(T)$ versus T are plotted in figures 1 to 3 for Ca XII, XVI, XIX lines. Obviously, the variation of $G(T)$ with T is sharp and the argument made by Pottasch is satisfied.

4. Discussion

The method for the calculation of line intensities discussed here can be applied to those lines in which the excited state is obtained by direct excitation from the ground

Table 1. Intensities of the x-ray lines of calcium ions (in erg $\mathrm{cm}^{-2}\ \mathrm{s}^{-1}$) and line temperatures.

Å	Ion	I	$T_{\max}$	$C_{gjd} = 0$	
				I	$T_{\max}$
2·70	Ca XIX	$5{\cdot}591^{-5}$*	$3{\cdot}0^{7}$	$4{\cdot}821^{-5}$	$3{\cdot}0^{7}$
3·17	Ca XIX	$3{\cdot}750^{-4}$	$3{\cdot}0^{7}$	$3{\cdot}263^{-4}$	$3{\cdot}0^{7}$
18·8	Ca XVIII	$2{\cdot}816^{-4}$	$7{\cdot}0^{6}$	$1{\cdot}495^{-4}$	$7{\cdot}0^{6}$
19·5	Ca XVII	$2{\cdot}892^{-4}$	$6{\cdot}0^{6}$	$2{\cdot}013^{-4}$	$5{\cdot}0^{6}$
21·4	Ca XVI	$4{\cdot}431^{-4}$	$5{\cdot}0^{6}$	$3{\cdot}467^{-4}$	$5{\cdot}0^{6}$
22·6	Ca XV	$6{\cdot}446^{-4}$	$5{\cdot}0^{6}$	$3{\cdot}958^{-4}$	$5{\cdot}0^{6}$
22·8	Ca XVI	$1{\cdot}598^{-5}$	$5{\cdot}0^{6}$	$1{\cdot}275^{-5}$	$5{\cdot}0^{6}$
24·1	Ca XIV	$6{\cdot}243^{-4}$	$3{\cdot}0^{6}$	$5{\cdot}023^{-4}$	$3{\cdot}0^{6}$
24·4	Ca XV	$1{\cdot}872^{-5}$	$5{\cdot}0^{6}$	$1{\cdot}196^{-5}$	$5{\cdot}0^{6}$
25·5	Ca XIII	$5{\cdot}579^{-4}$	$3{\cdot}0^{6}$	$4{\cdot}150^{-4}$	$3{\cdot}0^{6}$
26·5	Ca XIV	$2{\cdot}186^{-5}$	$3{\cdot}0^{6}$	$1{\cdot}805^{-5}$	$3{\cdot}0^{6}$
28·3	Ca XII	$1{\cdot}073^{-3}$	$2{\cdot}4^{6}$	$7{\cdot}687^{-4}$	$2{\cdot}4^{6}$
28·8	Ca XIII	$1{\cdot}659^{-5}$	$3{\cdot}0^{6}$	$1{\cdot}287^{-5}$	$3{\cdot}0^{6}$
30·87	Ca XI	$1{\cdot}033^{-3}$	$1{\cdot}9^{6}$	$7{\cdot}293^{-4}$	$1{\cdot}75^{6}$
32·0	Ca XII	$4{\cdot}458^{-5}$	$2{\cdot}5^{6}$	$3{\cdot}178^{-5}$	$2{\cdot}3^{6}$
35·21	Ca XI	$7{\cdot}472^{-5}$	$1{\cdot}9^{6}$	$5{\cdot}676^{-5}$	$1{\cdot}75^{6}$

*The superscript denotes the power of ten by which the number is to be multiplied e.g. $5{\cdot}591^{-5} = 5{\cdot}591 \times 10^{-5}$ and $3{\cdot}0^{7} = 3{\cdot}0 \times 10^{7}$.

state i.e. only for resonance lines. In the present investigation only resonance lines are considered.

It is observed that the optimum temperature $T_{\max}$ is not necessarily equal to that given by the peak of N_g/N_E (the ion abundance) distribution. Further, the temperature $T_{\max}$ for the line in both the sets is not necessarily equal (table 1). Table 1 also shows that the contribution of dielectronic recombination excitation for the lines under consideration varies from 15% to 88% of that of the electron impact excitation and is significant in the x-ray region. But it becomes much smaller in the ultraviolet region and negligible in the visible and infrared regions.

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References

Ansari S M R and Alam B 1975 *Solar Phys.* **41** 97
Ansari S M R, Elwert G and Mucklich P 1970 *Z. Naturforsch.* **25a** 1781
Burgess A 1964 *Astrophys. J.* **139** 776
Burgess A 1965 *Astrophys. J.* **141** 1588
Chandra S 1978 *Solar Phys.* **58** 291
Gabriel A H 1972 *Mon. Not. Roy. Astron. Soc.* **160** 99
Mason H E 1975 *Mon. Not. Roy. Astron. Soc.* **170** 651
Mewe R 1972 *Solar Phys.* **22** 459
Pottasch S R 1963 *Astrophys. J.* **137** 945
Van Regemorter H 1962 *Astrophys. J.* **136** 906
Van Rensbergen W 1967 *Solar Phys.* **1** 354