THE IONIZATION EQUILIBRIUM FOR IRON IN THE SOLAR CORONA

A. Burgess and M. J. Seaton

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Summary

It has been shown by Burgess that, when allowance is made for dielectronic processes, recombination rates for coronal ions are much larger than have hitherto been supposed. New calculations are made of the ionization equilibrium for iron. Although allowance for dielectronic processes results in the discrepancies being much reduced, it still appears that there may be some tendency for temperatures obtained from line-widths to be larger than those deduced from ionization theory.

The ionization equilibrium in the solar corona is determined by collisional ionization,

$$X^{+m}+e \rightarrow X^{+m+1}+e+e \tag{1}$$

with rate coefficient $q(X^{+m})$, and radiative recombination,

$$X^{+m+1}+e \rightarrow X^{+m}+h\nu \tag{2}$$

with rate coefficient $\alpha(X^{+m})$. By radiative recombination we mean any process in which the *complete* reaction is represented by (2). The ionization equilibrium, $N(X^{+m+1})/N(X^{+m})=q(X^{+m})/\alpha(X^{+m})$, depends on temperature but is independent of density. The ionization rate may be calculated with fair accuracy using the expression (1, 2)

$$q(X^{+m})=2\cdot 0\times 10^{-8}T^{1/2}\sum_{l}\frac{\zeta_m(nl)10^{-5440I_m(nl)/T}}{I_m^2(nl)}\ \mathrm{cm^2\,sec^{-1}} \tag{3}$$

where n is the principal quantum number of the outer electrons of X^{+m}, $\zeta_m(nl)$ is the number of electrons with quantum numbers nl, $I_m(nl)$ is the corresponding ionization potential in electron volts, and T is in °K. In all earlier work the recombination rate has been calculated on making the assumption that intermediate states do not have to be considered in (2); using hydrogenic data (3) one then obtains a rate coefficient which, for coronal ions, may be represented by

$$\alpha'(X^{+m})=\frac{1\cdot 3\times 10^{-9}(m+1)^2 I_m^{1/2}}{T}\ \mathrm{cm^3\,sec^{-1}}. \tag{4}$$

In 1961 it was suggested to us by Professor Unsöld that the reaction (2) might take place *via* unstable intermediate states of X^{+m} containing two electrons in excited orbitals. Calculations made by Burgess (4) for recombination of $Fe^{+15}2p^6 3s$ to $Fe^{+14}2p^6 3s^2$ show that allowance for such dielectronic processes gives a rate coefficient which, at coronal temperatures, is approximately proportional to $1/T$ and is about twenty times greater than the coefficient α' calculated from (4). Similar calculations are being made for other ions. In the present paper we give the results of some preliminary calculations of the iron ionization equilibrium.

The recombination rate calculated with allowance for dielectronic processes is, to about the same accuracy that (3) is valid, proportional to the number of outer shell electrons, ζ_{m+1}, of the recombining ion. For recombination of ions with outer $n=3$ electrons we take

$$\alpha(\mathrm{Fe}^{+m}) = 20\,\zeta_{m+1}\alpha'(\mathrm{Fe}^{+m}) \quad (m \leqslant 14) \tag{5}$$

where α' is given by (4) and where $\zeta_{m+1} = \sum_l \zeta_{m+1}(3l)$. A different expression is required for recombination of ions with outer $2p$ electrons. Results of some approximate calculations of $\alpha(\mathrm{Fe}^{+15})$ are given in Table 1 and for $m \geqslant 15$ we take

$$\alpha(\mathrm{Fe}^{+m}) = \frac{\zeta_{m+1}}{6}\alpha(\mathrm{Fe}^{+15}) \quad (m \geqslant 15) \tag{6}$$

where ζ_{m+1} is now the number of $2p$ electrons of the recombining ion.

TABLE I

Recombination to form Fe^{+15}

(T in °K, α in $cm^3\ sec^{-1}$)

$\log_{10} T$	$10^{11} \times \alpha\ (\mathrm{Fe}^{+15})$
6·2	0·6
6·3	1·3
6·4	2·2
6·5	3·2
6·6	4·1
6·7	4·5
6·8	4·7

Table II gives results for the ionization equilibrium calculated using (3), (5) and (6). For ionization from configurations $3s^2 3p^{\zeta(3p)} 3d^{\zeta(3d)}$ we take $I(3p)$ to exceed $I(3d)$ by 55 eV and $I(3s)$ to exceed $I(3p)$ by 35 eV. In Figure 1 the results are presented graphically for Fe^{+13} and Fe^{+9}, which produce the green [Fe XIV] line and the red [Fe X] line. The effect of the dielectronic process is to increase the temperature at which any given ion has maximum abundance and to make the ionization curves much less sharply peaked about their maxima. Both effects tend to reduce the discrepancies between ionization temperatures and temperatures deduced from line widths interpreted assuming thermal Doppler broadening. According to the latest results of Billings (5) the temperatures T(XIV) and T(X) obtained from the line widths are such that T(XIV) tends to exceed T(X) by about $0{\cdot}6 \times 10^6$ °K, and it therefore appears that they cannot be explained in terms of a simple isothermal model. For regions which are bright in both lines,

T(XIV) is close to $2\cdot5 \times 10^6$ °K and T(X) is about $1\cdot9 \times 10^6$ °K, and for more active regions in which the red line is dim, or in which the [Ca XV] yellow line may be seen, T(XIV) is equal to 3×10^6 °K or more. Comparing these results with those of Figure 1 it is seen that there still appears to be some tendency for the line width temperatures to be greater than the ionization temperatures. It may be noted that the temperature deduced from Doppler widths will be too large by factors of 1·5 if macroscopic motions in the corona account for only 0·5 per cent of the total kinetic energy. The flatter maxima of the new ion abundance curves make it easier to understand the observation of a range of line width temperatures for a given stage of ionization, and to understand observations of strong emission from several different stages of ionization originating in localized regions in which large temperature variations would not be expected.

TABLE II

Values of $\log_{10} \{N(\mathrm{Fe}^{+m})/N(\mathrm{Fe})\}$

$\log_{10} T$ \ m	8	9	10	11	12	13	14	15
5·9	$\bar{1}\cdot60$	$\bar{1}\cdot00$	$\bar{2}\cdot03$					
6·0	$\bar{1}\cdot61$	$\bar{1}\cdot48$	$\bar{1}\cdot01$	$\bar{2}\cdot20$				
6·1	$\bar{1}\cdot25$	$\bar{1}\cdot52$	$\bar{1}\cdot47$	$\bar{1}\cdot12$	$\bar{2}\cdot41$	$\bar{3}\cdot45$		
6·2	$\bar{2}\cdot52$	$\bar{1}\cdot13$	$\bar{1}\cdot46$	$\bar{1}\cdot50$	$\bar{1}\cdot21$	$\bar{2}\cdot71$	$\bar{3}\cdot95$	$\bar{4}\cdot98$
6·3	$\bar{3}\cdot41$	$\bar{2}\cdot33$	$\bar{2}\cdot98$	$\bar{1}\cdot37$	$\bar{1}\cdot45$	$\bar{1}\cdot34$	$\bar{1}\cdot00$	$\bar{2}\cdot47$
6·4		$\bar{3}\cdot10$	$\bar{2}\cdot04$	$\bar{2}\cdot74$	$\bar{1}\cdot15$	$\bar{1}\cdot38$	$\bar{1}\cdot40$	$\bar{1}\cdot27$
6·5			$\bar{4}\cdot80$	$\bar{3}\cdot77$	$\bar{2}\cdot48$	$\bar{1}\cdot01$	$\bar{1}\cdot35$	$\bar{1}\cdot55$
6·6				$\bar{4}\cdot71$	$\bar{3}\cdot67$	$\bar{2}\cdot47$	$\bar{1}\cdot10$	$\bar{1}\cdot60$
6·7					$\bar{4}\cdot84$	$\bar{3}\cdot89$	$\bar{2}\cdot77$	$\bar{1}\cdot54$
6·8							$\bar{2}\cdot37$	$\bar{1}\cdot39$

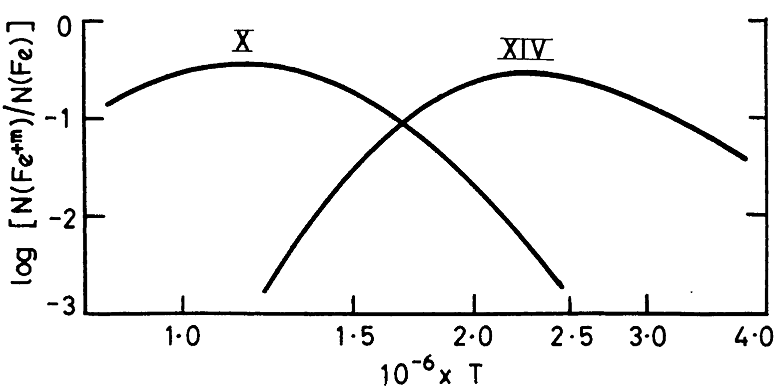

FIG. 1.—*The ionization equilibrium for Fe X and Fe XIV.*

The recombination process will generally not be an important mechanism for excitation of the forbidden lines, since the recombination rates are equal to the corresponding collisional ionization rates and the latter are generally small compared with the rates of collisional excitation. We have considered that excitation of Fe^{+m} forbidden lines by electron collisions may occur *via* unstable states of Fe^{+m-1}; this may lead to some increase in the excitation rates, but not by

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large factors. It would seem that allowance for dielectronic processes will not produce any large change in the abundances calculated (6) from forbidden line intensities.

Department of Physics,
University College,
London:
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