

DIELECTRONIC RECOMBINATION RATES, IONIZATION EQUILIBRIUM, AND RADIATIVE EMISSION RATES FOR CALCIUM AND NICKEL IONS IN LOW-DENSITY HIGH-TEMPERATURE PLASMAS

V. L. JACOBS, J. DAVIS, AND J. E. ROGERSON

Plasma Radiation Group, Plasma Physics Division, Naval Research Laboratory

M. BLAHA

Department of Physics and Astronomy, University of Maryland

AND

J. CAIN AND M. DAVIS

Science Applications, Inc., McLean, Virginia

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ABSTRACT

We have calculated the total dielectronic recombination rates for Ca and Ni ions, taking into account autoionization to excited states of the recombining ion and stabilizing radiative transitions of the recombining electron. Radiative transitions of the recombining ion are found to be the dominant stabilizing processes, and the relative importance of $\Delta n = 0$ and $\Delta n \neq 0$ transitions in the relevant temperature region is determined for each ion. The relative importance of the $\Delta n = 0$ and $\Delta n \neq 0$ contributions is significantly altered for some ions by the inclusion of autoionization to excited levels. The relative abundance of the various ionization stages has been determined by using a corona equilibrium model in which collisional ionization and inner-shell excitation followed by autoionization are balanced by direct radiative and dielectronic recombination. The power radiated by an optically thin low-density plasma has been calculated taking into account resonance line emission, direct recombination radiation, dielectronic recombination radiation, and bremsstrahlung. Results are also presented for some relative line intensities in Ca which exhibit a strong dependence on the electron temperature.

Subject headings: atomic processes — plasmas — transition probabilities

1. INTRODUCTION

The analysis of the optically thin far-ultraviolet and X-ray emission lines of multiply charged atomic ions has been one of the basic methods for determining the temperatures and densities of high-temperature astrophysical and laboratory plasmas. In addition, the energy balance in these plasmas can be significantly influenced by the emission of X-ray radiation from relatively low concentrations of multiply charged ions. Even when the plasma is assumed to be in an equilibrium state of excitation and ionization, the populations of the excited levels usually depart substantially from their local thermodynamic equilibrium values (Griem 1964). Consequently, the correct theoretical determination of the spectral line intensities requires a detailed treatment of many elementary collisional and radiative processes.

A substantial simplification in the theoretical determination of the spectral line intensities can be accomplished by the separation of the excitation and ionization balance problems. This separation is possible only in the corona model (McWhirter 1965), which is valid for highly charged ions in low-density plasmas. In this model one first determines the ionization structure, assuming that electron impact ionization and autoionization following inner-shell electron impact excitation from each ground state are balanced by direct radiative and dielectronic recombination. If the density dependence of the dielectronic recombination rates (Burgess and Summers 1969; Jacobs and Davis 1978) is ignored, these ionization-equilibrium distributions are independent of density and are functions of only the local electron temperature. The spectral line intensities emitted by the low-lying excited states, which are assumed to undergo spontaneous radiative decay in times that are short compared with the electron-ion collision times, are then evaluated by using the corona ionization-equilibrium distributions of the ground states and their electron impact excitation rates. Departures from the density independence of relative line intensities have been observed (Feldman and Doschek 1977) and must be attributed to collisional de-excitation competing with spontaneous radiative decay or to the effects of reabsorption of the emitted radiation.

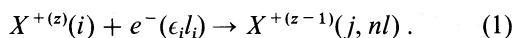
Even though the corona ionization-recombination balance problem represents a substantial simplification of the more general collisional-radiative equilibrium equations (McWhirter 1965), it is now recognized

as a much more complex problem than was first believed (House 1964). The increased complexity is the result of the discovery by Burgess (1964) that the dominant recombination process for incompletely ionized ions in the important temperature region is the process of dielectronic recombination, which occurs through very highly excited states of the recombined ion. Burgess (1965) was able to derive a simple formula for estimating the total dielectronic recombination rates in a low-density plasma, and this formula has been employed to include dielectronic recombination in ionization-equilibrium calculations (Jordan 1969, 1970). We have been engaged in a more detailed treatment of dielectronic recombination (Jacobs *et al.* 1977a, b; Davis *et al.* 1977) and have discovered that the widely used formula of Burgess (1965) can substantially overestimate the dielectronic recombination rates for certain states of ionization because of the neglect of autoionization into continuum channels corresponding to excited states of the recombining ion. In this investigation, we have extended our calculations to allow for stabilizing radiative transitions of the recombining electron in addition to the stabilizing radiative transitions of the recombining ion core. It has become apparent from our investigation that the correct determination of the dielectronic recombination rates requires a detailed treatment in which several autoionization and radiative stabilization processes are taken into account.

In § II we outline the extended version of the theory of dielectronic recombination and present the results of our calculations of the total dielectronic recombination rates for Ca and Ni ions. Particular emphasis is given to the effect of autoionization to excited states on the relative importance of $\Delta n = 0$ and $\Delta n \neq 0$ stabilizing radiative transitions of the recombining ion core. In § III we present the results of our calculations for the corona ionization equilibrium abundances which were obtained by using the new dielectronic recombination rates. In § IV, we give our results for the radiative emission rates for resonance line radiation, direct recombination radiation, dielectronic recombination radiation, and bremsstrahlung. Results are also presented for the temperature dependence of some relative line intensities in Ca. Our conclusions are discussed in § V.

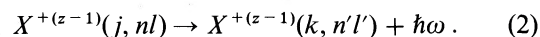
II. DIELECTRONIC RECOMBINATION

The dielectronic recombination of the ion $X^{+(z)}$ with residual charge z may be described as a two-step process (Burgess 1964). First there is a radiationless capture of a plasma electron into an nl state accompanied by the excitation $i \rightarrow j$ of the recombining ion core:



The initial state i is usually assumed to be the ground state g . Recombination is accomplished if, instead of autoionizing, the doubly excited state j, nl undergoes a stabilizing radiative transition to a final state $k, n'l'$

which occurs below the ionization threshold:



The multi-electron states i, j , and k will be specified in this investigation by giving only the effective principal and orbital angular momentum quantum numbers of the active electron. The spectator electrons will, however, be taken into account in the evaluation of the transition rates.

As has been emphasized by Burgess (1964), the dielectronic recombination of the astrophysically abundant ions, for which Z is usually less than 20, occurs primarily through highly excited nl states of the recombining electron. Accordingly, the dominant stabilization process is assumed to be a $j \rightarrow g$ radiative de-excitation of the recombining ion core, i.e., $n'l' = nl$ and k is the ground state configuration. In addition, the most probable stabilizing de-excitation of the recombining ion is usually associated with a $\Delta n_j = 0$ transition of the active electron. Because the radiative decay rates for $\Delta n_j = 0$ transitions increase only as z , the outer-electron stabilizing transition rates, which scale as z^4 , might be expected to become more important with increasing z . In order to make a correct assessment of the importance of these additional stabilizing transitions, it will be necessary to take into account both $\Delta n_i = 0$ and $\Delta n_i \neq 0$ excitations of the recombining ion.

For a Maxwellian distribution of electron velocities the dielectronic recombination rate coefficient associated with a given final state $k, n'l'$ can be expressed in the form (Shore 1969):

$$\begin{aligned} \alpha_d(i \rightarrow k, n'l') &= 2^3 a_0^3 \pi^{3/2} (E_H/k_B T_e)^{3/2} \sum_{j, nl} \frac{g(j, nl)}{2g(i)} \\ &\times \frac{A_a(j, nl \rightarrow i, \epsilon_i) A_r(j, nl \rightarrow k, n'l')}{A(j, nl)} \\ &\times \exp \left[\frac{E(i) - E(j, nl)}{k_B T_e} \right], \end{aligned} \quad (3)$$

where the statistical weights associated with the levels with energies $E(i)$ and $E(j, nl)$ are denoted by $g(i)$ and $g(j, nl)$, respectively, and the other symbols have their conventional meanings. The assumption that all important final states $k, n'l'$ cascade freely to the ground state allows the total dielectronic recombination rate to be expressed, in terms of the total dielectronic recombination rate coefficient,

$$\alpha_d(z, i) = \sum_{k, n'l'} \alpha_d(i \rightarrow k, n'l'), \quad (4)$$

in the form

$$R_d(z, i) = N_e N(z, i) \alpha_d(z, i), \quad (5)$$

where the electron and initial ion densities are denoted by N_e and $N(z, i)$, respectively. In the corona model approximation which is employed in this investigation, the recombining ions are assumed to be initially in their ground state configurations, i.e., $i = g$.

Dielectronic recombination of lithium-like ions following the $\Delta n_i = 0$ excitation can occur by means of stabilizing radiative transitions of the type $2p, nl \rightarrow 2p, n'l'$, which terminate in a doubly excited bound state only for relatively small values of n' . The corresponding contribution has been found to represent only between 8% and 20% of the total for the $2s \rightarrow 2p$ excitation in Fe xxiv (Raymond 1978), which is within the accuracy usually expected from the Burgess (1965) formula. In the case of $\Delta n_i \neq 0$ excitations of the recombining ion, stabilizing transitions of the recombining electron to singly excited bound states are expected to become more important with increasing z , because the important stabilizing transitions following $\Delta n_i \neq 0$ excitations will occur predominantly from doubly excited states corresponding to lower values of the outer-electron principal quantum number n .

When all possible stabilizing radiative transitions are taken into account, the consistent calculation of

the total dielectronic recombination rate coefficient becomes a much more complex problem. In order to simplify this calculation, we have taken into account only transitions to singly excited final states. These transitions can occur for both $\Delta n_i = 0$ and $\Delta n_i \neq 0$ excitations of the recombining ion. The autoionization rates $A_a(j, nl \rightarrow i, \epsilon_i)$ for the entire Rydberg series of doubly excited states j, nl are most conveniently obtained from the threshold values of the partial-wave electron-impact excitation cross sections $\sigma(i, \epsilon_i l_i \rightarrow j, \epsilon_j l_j)$ by means of the quantum-defect theory relationship derived by Seaton (1969). All stabilizing radiative decay rates $A_r(j, nl \rightarrow k, n'l')$ are expressible in terms of the corresponding rates describing the active-electron transition, i.e., $A_r(j \rightarrow k)$ for $n'l' = nl$ and $A_r(nl \rightarrow n'l')$ for stabilizing transitions of the recombining electron.

The total decay rate $A(j, nl)$ is obtained as the sum of the autoionization rates $A_a(j, nl \rightarrow k, \epsilon_k)$ into all

TABLE 1
STABILIZING RADIATIVE TRANSITIONS OF RECOMBINING ION IN ORDER OF DECREASING IMPORTANCE AT
TEMPERATURE OF MAXIMUM EQUILIBRIUM ABUNDANCE

Recombining Ion	Active Electron Transitions			
Ca II	$4p \rightarrow 4s$	$5p \rightarrow 4s$	...	...
Ca III	$3d \rightarrow 3p$	$4s \rightarrow 3p$	$4d \rightarrow 3p^a$	...
Ca IV	$3d \rightarrow 3p$	$3p \rightarrow 3s$	$4s \rightarrow 3p$	$4d \rightarrow 3p^a$
Ca V	$3d \rightarrow 3p$	$3p \rightarrow 3s$	$4s \rightarrow 3p$	$4d \rightarrow 3p^a$
Ca VI	$3d \rightarrow 3p$	$3p \rightarrow 3s$	$4s \rightarrow 3p$	$4d \rightarrow 3p^a$
Ca VII	$3d \rightarrow 3p$	$3p \rightarrow 3s$	$4s \rightarrow 3p$	$4d \rightarrow 3p^a$
Ca VIII	$3p \rightarrow 3s$	$3d \rightarrow 3p$	$4s \rightarrow 3p$	$4d \rightarrow 3p^a$
Ca IX	$3p \rightarrow 3s$	$4p \rightarrow 3s^a$	...	...
Ca X	$3p \rightarrow 3s$	$4p \rightarrow 3s^a$	...	...
Ca XI	$3s \rightarrow 2p$	$3d \rightarrow 2p^a$	...	...
Ca XII	$2p \rightarrow 2s$	$3d \rightarrow 2p^a$	$3s \rightarrow 2p$	...
Ca XIII	$2p \rightarrow 2s$	$3d \rightarrow 2p^a$	$3s \rightarrow 2p$	...
Ca XIV	$2p \rightarrow 2s$	$3d \rightarrow 2p^a$	$3s \rightarrow 2p$	...
Ca XV	$2p \rightarrow 2s$	$3d \rightarrow 2p^a$	$3s \rightarrow 2p$	...
Ca XVI	$2p \rightarrow 2s$	$3d \rightarrow 2p^a$	$3s \rightarrow 2p$	...
Ca XVII	$2p \rightarrow 2s$	$3p \rightarrow 2s^a$	...	...
Ca XVIII	$2p \rightarrow 2s$	$3p \rightarrow 2s^a$	...	...
Ca XIX	$2p \rightarrow 1s$	$3p \rightarrow 1s^a$	...	...
Ca XX	$2p \rightarrow 1s$	$3p \rightarrow 1s$	...	...
Ni XI	$3d \rightarrow 3p$	$4s \rightarrow 3p$	$4d \rightarrow 3p^a$	...
Ni XII	$3d \rightarrow 3p$	$3p \rightarrow 3s$	$4s \rightarrow 3p$	$4d \rightarrow 3p^a$
Ni XIII	$3d \rightarrow 3p$	$3p \rightarrow 3s$	$4s \rightarrow 3p$	$4d \rightarrow 3p^a$
Ni XIV	$3d \rightarrow 3p$	$3p \rightarrow 3s$	$4s \rightarrow 3p$	$4d \rightarrow 3p^a$
Ni XV	$3d \rightarrow 3p$	$3p \rightarrow 3s$	$4s \rightarrow 3p$	$4d \rightarrow 3p^a$
Ni XVI	$3p \rightarrow 3s$	$3d \rightarrow 3p$	$4s \rightarrow 3p$	$4d \rightarrow 3p^a$
Ni XVII	$3p \rightarrow 3s$	$4p \rightarrow 3s^a$	...	...
Ni XVIII	$3p \rightarrow 3s$	$4p \rightarrow 3s^a$	...	...
Ni XIX	$3s \rightarrow 2p$	$3d \rightarrow 2p^a$	...	...
Ni XX	$3d \rightarrow 2p^a$	$2p \rightarrow 2s$	$3s \rightarrow 2p$	...
Ni XXI	$3d \rightarrow 2p^a$	$2p \rightarrow 2s$	$3s \rightarrow 2p$	...
Ni XXII	$3d \rightarrow 2p^a$	$2p \rightarrow 2s$	$3s \rightarrow 2p$	...
Ni XXIII	$2p \rightarrow 2s$	$3d \rightarrow 2p^a$	$3s \rightarrow 2p$	...
Ni XXIV	$2p \rightarrow 2s$	$3d \rightarrow 2p^a$	$3s \rightarrow 2p$	...
Ni XXV	$2p \rightarrow 2s$	$3p \rightarrow 2s^a$	...	...
Ni XXVI	$2p \rightarrow 2s$	$3p \rightarrow 2s^a$	...	...
Ni XXVII	$2p \rightarrow 1s$	$3p \rightarrow 1s^a$	...	...
Ni XXVIII	$2p \rightarrow 1s$	$3p \rightarrow 1s$	...	...

^a Affected by autoionization accompanied by excitation.

lower states $k < j$ of the recombining ion and the radiative transition rates $A_r(j, nl \rightarrow k, n'l')$ to all final states $k, n'l'$ below the ionization threshold:

$$A(j, nl) = \sum_{k < j} \left[A_a(j, nl \rightarrow k, \epsilon_k) + \sum_{n'l' \leq nl} A_r(j, nl \rightarrow k, n'l') \right]. \quad (6)$$

When radiative transitions to final states $k, n'l'$ which occur above the ionization threshold are found to be important, these same transitions must also be con-

sidered as a process for populating the doubly excited states j, nl .

The most important innovation in our treatment of dielectronic recombination (Jacobs *et al.* 1977*a, b*; Davis *et al.* 1977) has been the inclusion of autoionization into continuum channels corresponding to excited states k of the recombining ion. When such an autoionization process can occur through a $\Delta n_j = 0$ dipole transition, it can have a substantially higher probability than the true inverse of the radiationless capture process (1). Since radiationless electron capture from the excited state is ignored in the corona

TABLE 2
DIELECTRONIC RECOMBINATION RATE COEFFICIENTS (in $\text{cm}^3 \text{s}^{-1}$) FOR Ca IONS

$\log_{10} T_e \text{ (K)}$	IONS					
	Ca II	Ca III	Ca IV	Ca V	Ca VI	Ca VII
4.0	0.10 (-10) ^a	0.89 (-23)	0.38 (-13)	0.61 (-13)	0.15 (-12)	0.94 (-11)
4.2	0.19 (-10)	0.14 (-17)	0.16 (-12)	0.40 (-12)	0.93 (-12)	0.20 (-10)
4.4	0.22 (-10)	0.34 (-14)	0.50 (-12)	0.17 (-11)	0.35 (-11)	0.31 (-10)
4.6	0.18 (-10)	0.45 (-12)	0.27 (-11)	0.84 (-11)	0.15 (-10)	0.45 (-10)
4.8	0.31 (-10)	0.81 (-11)	0.15 (-10)	0.32 (-10)	0.53 (-10)	0.88 (-10)
5.0	0.79 (-11)	0.40 (-10)	0.61 (-10)	0.94 (-10)	0.13 (-9)	0.17 (-9)
5.2	0.45 (-11)	0.84 (-10)	0.13 (-9)	0.18 (-9)	0.21 (-9)	0.26 (-9)
5.4	0.25 (-11)	0.11 (-9)	0.17 (-9)	0.22 (-9)	0.25 (-9)	0.26 (-9)
5.6	0.13 (-11)	0.94 (-10)	0.16 (-9)	0.20 (-9)	0.22 (-9)	0.23 (-9)
5.8	0.67 (-12)	0.68 (-10)	0.12 (-9)	0.15 (-9)	0.16 (-9)	0.16 (-9)
6.0	0.34 (-12)	0.43 (-10)	0.75 (-10)	0.96 (-10)	0.98 (-10)	0.99 (-10)
6.2	0.17 (-12)	0.25 (-10)	0.44 (-10)	0.56 (-10)	0.57 (-10)	0.57 (-10)
6.4	0.88 (-13)	0.14 (-10)	0.24 (-10)	0.31 (-10)	0.31 (-10)	0.31 (-10)
6.6	0.45 (-13)	0.73 (-11)	0.13 (-10)	0.17 (-10)	0.17 (-10)	0.17 (-10)
6.8	0.22 (-13)	0.38 (-11)	0.67 (-11)	0.87 (-11)	0.87 (-11)	0.86 (-11)
7.0	0.11 (-13)	0.19 (-11)	0.35 (-11)	0.45 (-11)	0.45 (-11)	0.44 (-11)
7.2	0.56 (-14)	0.98 (-12)	0.18 (-11)	0.23 (-11)	0.23 (-11)	0.22 (-11)
7.4	0.28 (-14)	0.50 (-12)	0.98 (-12)	0.11 (-11)	0.11 (-11)	0.11 (-11)
7.6	0.14 (-14)	0.25 (-12)	0.45 (-12)	0.58 (-12)	0.58 (-12)	0.57 (-12)
7.8	0.71 (-15)	0.13 (-12)	0.23 (-12)	0.29 (-12)	0.29 (-12)	0.29 (-12)
8.0	0.36 (-15)	0.63 (-13)	0.11 (-12)	0.15 (-12)	0.15 (-12)	0.14 (-12)
	Ca VIII	Ca IX	Ca X	Ca XI	Ca XII	Ca XIII
4.0	0.87 (-10)	0.68 (-10)	0.22 (-11)	0.00 (-0)	0.13 (-18)	0.18 (-9)
4.2	0.94 (-10)	0.97 (-10)	0.79 (-11)	0.00 (-0)	0.17 (-15)	0.13 (-9)
4.4	0.81 (-10)	0.99 (-10)	0.16 (-10)	0.17 (-49)	0.13 (-13)	0.80 (-10)
4.6	0.69 (-10)	0.94 (-10)	0.30 (-10)	0.65 (-35)	0.14 (-12)	0.46 (-10)
4.8	0.94 (-10)	0.13 (-9)	0.70 (-10)	0.81 (-26)	0.54 (-12)	0.26 (-10)
5.0	0.18 (-9)	0.23 (-9)	0.12 (-9)	0.34 (-20)	0.11 (-11)	0.15 (-10)
5.2	0.28 (-9)	0.30 (-9)	0.15 (-9)	0.97 (-17)	0.24 (-11)	0.12 (-10)
5.4	0.30 (-9)	0.29 (-9)	0.13 (-9)	0.13 (-14)	0.55 (-11)	0.16 (-10)
5.6	0.25 (-9)	0.22 (-9)	0.92 (-10)	0.29 (-13)	0.92 (-11)	0.22 (-10)
5.8	0.17 (-9)	0.15 (-9)	0.58 (-10)	0.24 (-12)	0.11 (-10)	0.23 (-10)
6.0	0.11 (-9)	0.88 (-10)	0.34 (-10)	0.92 (-12)	0.97 (-11)	0.20 (-10)
6.2	0.60 (-10)	0.49 (-10)	0.18 (-10)	0.18 (-11)	0.82 (-11)	0.15 (-10)
6.4	0.33 (-10)	0.26 (-10)	0.98 (-11)	0.98 (-11)	0.23 (-11)	0.11 (-10)
6.6	0.17 (-10)	0.14 (-10)	0.51 (-11)	0.20 (-11)	0.49 (-11)	0.79 (-11)
6.8	0.90 (-11)	0.71 (-11)	0.26 (-11)	0.15 (-11)	0.33 (-11)	0.51 (-11)
7.0	0.46 (-11)	0.36 (-11)	0.31 (-11)	0.94 (-12)	0.20 (-11)	0.31 (-11)
7.2	0.23 (-11)	0.18 (-11)	0.67 (-12)	0.55 (-12)	0.11 (-11)	0.18 (-11)
7.4	0.12 (-11)	0.93 (-12)	0.34 (-12)	0.30 (-12)	0.62 (-12)	0.96 (-12)
7.6	0.60 (-12)	0.47 (-12)	0.17 (-12)	0.16 (-12)	0.33 (-12)	0.51 (-12)
7.8	0.30 (-12)	0.24 (-12)	0.86 (-13)	0.84 (-13)	0.17 (-12)	0.26 (-12)
8.0	0.15 (-12)	0.12 (-12)	0.43 (-13)	0.43 (-13)	0.88 (-13)	0.13 (-12)

TABLE 2—Continued

$\log_{10} T_e$ (K)	IONS						
	Ca xiv	Ca xv	Ca xvi	Ca xvii	Ca xviii	Ca xix	Ca xx
4.0	0.87 (–11)	0.14 (–17)	0.50 (–13)	0.64 (–12)	0.10 (–25)	0.00 (–10)	0.00 (–0)
4.2	0.22 (–10)	0.15 (–14)	0.14 (–11)	0.84 (–11)	0.29 (–19)	0.00 (–0)	0.00 (–0)
4.4	0.31 (–10)	0.93 (–13)	0.85 (–11)	0.33 (–10)	0.27 (–15)	0.00 (–0)	0.00 (–0)
4.6	0.29 (–10)	0.10 (–11)	0.21 (–10)	0.63 (–10)	0.65 (–13)	0.00 (–0)	0.00 (–0)
4.8	0.23 (–10)	0.38 (–11)	0.31 (–10)	0.78 (–10)	0.16 (–11)	0.00 (–0)	0.00 (–0)
5.0	0.18 (–10)	0.86 (–11)	0.35 (–10)	0.79 (–10)	0.96 (–11)	0.00 (–0)	0.00 (–0)
5.2	0.20 (–10)	0.18 (–10)	0.41 (–10)	0.81 (–10)	0.23 (–10)	0.00 (–0)	0.00 (–0)
5.4	0.29 (–10)	0.35 (–10)	0.57 (–10)	0.95 (–10)	0.31 (–10)	0.00 (–0)	0.00 (–0)
5.6	0.37 (–10)	0.49 (–10)	0.72 (–10)	0.10 (–9)	0.28 (–10)	0.46 (–44)	0.32 (–45)
5.8	0.35 (–10)	0.50 (–10)	0.69 (–10)	0.87 (–10)	0.21 (–10)	0.30 (–31)	0.46 (–32)
6.0	0.27 (–10)	0.40 (–10)	0.54 (–10)	0.63 (–10)	0.14 (–10)	0.28 (–23)	0.70 (–24)
6.2	0.19 (–10)	0.29 (–10)	0.38 (–10)	0.40 (–10)	0.80 (–11)	0.24 (–18)	0.80 (–19)
6.4	0.14 (–10)	0.20 (–10)	0.26 (–10)	0.23 (–10)	0.46 (–11)	0.23 (–15)	0.99 (–16)
6.6	0.94 (–11)	0.13 (–10)	0.17 (–10)	0.13 (–10)	0.26 (–11)	0.14 (–13)	0.72 (–14)
6.8	0.61 (–11)	0.85 (–11)	0.11 (–10)	0.71 (–11)	0.15 (–11)	0.15 (–12)	0.91 (–13)
7.0	0.37 (–11)	0.51 (–11)	0.66 (–11)	0.38 (–11)	0.84 (–12)	0.52 (–12)	0.38 (–12)
7.2	0.21 (–11)	0.29 (–11)	0.37 (–11)	0.20 (–11)	0.46 (–12)	0.91 (–12)	0.74 (–12)
7.4	0.12 (–11)	0.16 (–11)	0.20 (–11)	0.10 (–11)	0.24 (–12)	0.10 (–11)	0.89 (–12)
7.6	0.62 (–12)	0.82 (–12)	0.11 (–11)	0.52 (–12)	0.13 (–12)	0.83 (–12)	0.79 (–12)
7.8	0.32 (–12)	0.43 (–12)	0.56 (–12)	0.26 (–12)	0.66 (–13)	0.58 (–12)	0.57 (–12)
8.0	0.17 (–12)	0.22 (–12)	0.29 (–12)	0.13 (–12)	0.33 (–13)	0.35 (–12)	0.36 (–12)

^a Numbers in parentheses are powers of 10.

model approximation, the inclusion of the additional autoionization rate in equation (6) must lead to a reduction in the contribution to $\alpha_d(z, i)$ which is associated with the higher excited state j . For certain ionization stages, this reduction is found to be important in the temperature region of maximum ionic abundance.

We have calculated the total dielectronic recombination rate coefficient for all of the incompletely stripped ions of Ca and for Ni xi through Ni xxviii. We have taken into account all stabilizing radiative transitions of both the recombining ion and the recombining electron which involve an electric-dipole transition of the active electron and terminate in a singly excited state of the recombined ion. The stabilizing radiative transitions of the recombining ion, which correspond to the inverse of the excitation process accompanying the initial radiationless capture, are listed in Table 1 for each ion in order of decreasing importance at the maximum abundance temperature which is predicted by the present calculations (see Table 6). The present assessment of the importance of each transition of the recombining ion in Table 1 takes into account the contribution from the radiative decay of the recombining electron. However, in none of the cases is this additional contribution found to produce an enhancement of the recombination rate which exceeds the expected accuracy of the Burgess formula. On the other hand, the relative importance of the $\Delta n_j = 0$ and $\Delta n_j \neq 0$ contributions is altered for certain ions by the inclusion of the rates for autoionization into an excited state of the recombining ion; and the ^a has been employed in Table 1 to identify the transitions whose contributions to α_d are affected by autoionization to

excited states. An important correction in the present calculation has been made for the case of $2p \rightarrow 1s$ transitions of the helium-like ion, where the $2p, nl \rightarrow 2s, \ell l'$ autoionization process is now assumed to be not energetically permissible for the most important outer electron levels. For He-like Fe α_d (Jacobs *et al.* 1977a) was probably underestimated by about 50%. All autoionization rates have been evaluated by using the threshold values of the partial-wave electron-impact excitation cross sections calculated by the distorted wave method (Davis, Kepple, and Blaha 1976).

In Tables 2 and 3 the total dielectronic recombination rate coefficients, which are defined by equation (4), are tabulated as functions of temperature for the ions of Ca and Ni. The simple formula derived by Burgess (1965) was also evaluated for each transition in Table 1, using our nonhydrogenic transition energies and oscillator strengths; and satisfactory agreement was obtained for the contribution from the radiative transition of the recombining ion only in the $\Delta n_j = 0$ case. The temperature dependence of the individual contributions to $\alpha_d(z, i)$ is similar to what has been shown in our previous papers (Jacobs *et al.* 1977a, b) for Fe and Si ions. The contribution from the $3d \rightarrow 2p$ transition of the recombining ion, which is the dominant contribution for Ni xx–Ni xxii, is about an order of magnitude smaller than would be predicted without the inclusion of the $3d, nl \rightarrow 3p, \ell l'$ autoionization rates, e.g., by the use of the Burgess formula.

III. CORONA IONIZATION EQUILIBRIUM

The distribution of the ions with atomic number Z over the various stages of ionization can be determined

TABLE 3
DIELECTRONIC RECOMBINATION RATE COEFFICIENTS (in $\text{cm}^3 \text{s}^{-1}$) FOR Ni IONS

$\log_{10} T_e \text{ (K)}$	IONS					
	Ni xi	Ni xii	Ni xiii	Ni xiv	Ni xv	Ni xvi
5.0	0.27 (-10) ^a	0.11 (-9)	0.75 (-10)	0.14 (-9)	0.12 (-9)	0.17 (-9)
5.2	0.87 (-10)	0.17 (-9)	0.15 (-9)	0.22 (-9)	0.18 (-9)	0.23 (-9)
5.4	0.22 (-9)	0.28 (-9)	0.28 (-9)	0.32 (-9)	0.30 (-9)	0.33 (-9)
5.6	0.36 (-9)	0.39 (-9)	0.36 (-9)	0.34 (-9)	0.33 (-9)	0.33 (-9)
5.8	0.41 (-9)	0.41 (-9)	0.39 (-9)	0.36 (-9)	0.36 (-9)	0.33 (-9)
6.0	0.35 (-9)	0.33 (-9)	0.31 (-9)	0.28 (-9)	0.28 (-9)	0.24 (-9)
6.2	0.25 (-9)	0.23 (-9)	0.21 (-9)	0.18 (-9)	0.18 (-9)	0.15 (-9)
6.4	0.15 (-9)	0.14 (-9)	0.13 (-9)	0.11 (-9)	0.11 (-9)	0.89 (-10)
6.6	0.88 (-10)	0.80 (-10)	0.74 (-10)	0.63 (-10)	0.61 (-10)	0.50 (-10)
6.8	0.48 (-10)	0.44 (-10)	0.40 (-10)	0.34 (-10)	0.33 (-10)	0.27 (-10)
7.0	0.26 (-10)	0.23 (-10)	0.21 (-10)	0.18 (-10)	0.17 (-10)	0.14 (-10)
7.2	0.13 (-10)	0.12 (-10)	0.11 (-10)	0.93 (-11)	0.89 (-11)	0.72 (-11)
7.4	0.68 (-11)	0.61 (-11)	0.57 (-11)	0.48 (-11)	0.46 (-11)	0.36 (-11)
7.6	0.35 (-11)	0.31 (-11)	0.29 (-11)	0.24 (-11)	0.23 (-11)	0.18 (-11)
7.8	0.18 (-11)	0.16 (-11)	0.15 (-11)	0.12 (-11)	0.12 (-11)	0.93 (-12)
8.0	0.88 (-12)	0.79 (-12)	0.73 (-12)	0.62 (-12)	0.59 (-12)	0.47 (-12)
8.2	0.44 (-12)	0.40 (-12)	0.37 (-12)	0.31 (-12)	0.30 (-12)	0.24 (-12)
8.4	0.22 (-12)	0.20 (-12)	0.19 (-12)	0.16 (-12)	0.15 (-12)	0.12 (-12)
	Ni xvii	Ni xviii	Ni xix	Ni xx	Ni xxi	Ni xxii
5.0	0.14 (-9)	0.37 (-10)	0.29 (-30)	0.81 (-12)	0.67 (-11)	0.20 (-10)
5.2	0.22 (-9)	0.97 (-10)	0.65 (-23)	0.19 (-11)	0.88 (-11)	0.20 (-10)
5.4	0.31 (-9)	0.14 (-9)	0.23 (-18)	0.35 (-11)	0.11 (-10)	0.22 (-10)
5.6	0.34 (-9)	0.13 (-9)	0.15 (-15)	0.66 (-11)	0.16 (-10)	0.29 (-10)
5.8	0.28 (-9)	0.10 (-9)	0.92 (-14)	0.98 (-11)	0.22 (-10)	0.35 (-10)
6.0	0.19 (-9)	0.66 (-10)	0.12 (-12)	0.11 (-10)	0.23 (-10)	0.32 (-10)
6.2	0.12 (-9)	0.39 (-10)	0.68 (-12)	0.94 (-11)	0.19 (-10)	0.25 (-10)
6.4	0.68 (-10)	0.22 (-10)	0.21 (-11)	0.79 (-11)	0.14 (-10)	0.18 (-10)
6.6	0.37 (-10)	0.12 (-10)	0.38 (-11)	0.72 (-11)	0.11 (-10)	0.14 (-10)
6.8	0.20 (-10)	0.62 (-11)	0.45 (-11)	0.65 (-11)	0.87 (-11)	0.11 (-10)
7.0	0.10 (-10)	0.32 (-11)	0.39 (-11)	0.51 (-11)	0.65 (-11)	0.81 (-11)
7.2	0.52 (-11)	0.16 (-11)	0.28 (-11)	0.35 (-11)	0.43 (-11)	0.55 (-11)
7.4	0.26 (-11)	0.83 (-12)	0.17 (-11)	0.22 (-11)	0.26 (-11)	0.33 (-11)
7.6	0.13 (-11)	0.42 (-12)	0.10 (-11)	0.12 (-11)	0.15 (-11)	0.19 (-11)
7.8	0.67 (-12)	0.21 (-12)	0.55 (-12)	0.68 (-12)	0.83 (-12)	0.10 (-11)
8.0	0.34 (-12)	0.11 (-12)	0.29 (-12)	0.36 (-12)	0.44 (-12)	0.56 (-12)
8.2	0.17 (-12)	0.53 (-13)	0.15 (-12)	0.19 (-12)	0.23 (-12)	0.29 (-12)
8.4	0.85 (-13)	0.27 (-13)	0.78 (-13)	0.96 (-13)	0.12 (-12)	0.15 (-12)
	Ni xxiii	Ni xxiv	Ni xxv	Ni xxvi	Ni xxvii	Ni xxviii
5.0	0.21 (-10)	0.11 (-10)	0.18 (-9)	0.16 (-11)	0.00 (-0)	0.00 (-0)
5.2	0.28 (-10)	0.23 (-10)	0.15 (-9)	0.85 (-11)	0.00 (-0)	0.00 (-0)
5.4	0.32 (-10)	0.34 (-10)	0.12 (-9)	0.19 (-10)	0.00 (-0)	0.00 (-0)
5.6	0.38 (-10)	0.47 (-10)	0.10 (-9)	0.25 (-10)	0.00 (-0)	0.00 (-0)
5.8	0.48 (-10)	0.62 (-10)	0.98 (-10)	0.23 (-10)	0.12 (-52)	0.17 (-53)
6.0	0.52 (-10)	0.66 (-10)	0.82 (-10)	0.17 (-10)	0.10 (-36)	0.24 (-37)
6.2	0.46 (-10)	0.56 (-10)	0.59 (-10)	0.11 (-10)	0.88 (-27)	0.28 (-27)
6.4	0.34 (-10)	0.40 (-10)	0.38 (-10)	0.63 (-11)	0.13 (-20)	0.49 (-21)
6.6	0.24 (-10)	0.26 (-10)	0.22 (-10)	0.36 (-11)	0.75 (-17)	0.33 (-17)
6.8	0.16 (-10)	0.17 (-10)	0.12 (-10)	0.22 (-11)	0.14 (-14)	0.70 (-15)
7.0	0.11 (-10)	0.10 (-10)	0.67 (-11)	0.13 (-11)	0.31 (-13)	0.17 (-13)
7.2	0.68 (-11)	0.61 (-11)	0.36 (-11)	0.81 (-12)	0.17 (-12)	0.10 (-12)
7.4	0.40 (-11)	0.34 (-11)	0.19 (-11)	0.47 (-12)	0.40 (-12)	0.27 (-12)
7.6	0.22 (-11)	0.19 (-11)	0.98 (-12)	0.26 (-12)	0.55 (-12)	0.39 (-12)
7.8	0.12 (-11)	0.10 (-11)	0.50 (-12)	0.14 (-12)	0.52 (-12)	0.39 (-12)
8.0	0.62 (-12)	0.52 (-12)	0.25 (-12)	0.75 (-13)	0.39 (-12)	0.30 (-12)
8.2	0.32 (-12)	0.27 (-12)	0.13 (-12)	0.39 (-13)	0.25 (-12)	0.20 (-12)
8.4	0.16 (-12)	0.14 (-12)	0.65 (-13)	0.20 (-13)	0.15 (-12)	0.12 (-12)

^a Numbers in parentheses are powers of 10.

TABLE 4
 $\log_{10} N(z)/N_z$ FOR Ca IONS

$\log_{10} T_e$ (K)	Ca I	Ca II	Ca III	Ca IV	Ca V	Ca VI	Ca VII	Ca VIII	Ca IX	Ca X	Ca XI	Ca XII	Ca XIII	Ca XIV	Ca XV	Ca XVI	Ca XVII	Ca XVIII	Ca XIX	Ca XX	Ca XXI
4.0	0.87	0.06	1.84	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
4.1	1.47	0.15	0.56	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
4.2	2.54	0.78	0.08	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
4.3	3.78	1.62	0.01	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
4.4	4.88	2.36	0.00	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
4.5	...	2.95	0.00	4.55	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
4.6	...	3.18	0.00	3.03	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
4.7	...	3.04	0.00	1.97	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
4.8	...	2.89	0.02	1.24	4.31	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
4.9	...	2.84	0.08	0.74	2.91	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
5.0	...	2.91	0.21	0.42	1.88	4.54	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
5.1	...	3.10	0.42	0.25	1.13	3.00	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
5.2	...	3.43	0.74	0.24	0.63	1.85	4.20	...	...	...	...	...	...	...	...	...	...	...	...	...	...
5.3	...	3.92	1.18	0.38	0.36	1.03	2.66	...	...	...	...	...	...	...	...	...	...	...	...	...	...
5.4	...	4.59	1.79	0.71	0.32	0.53	1.54	3.23	...	...	...	...	...	...	...	...	...	...	...	...	...
5.5	...	...	2.56	1.23	0.52	0.32	0.81	1.89	3.55	...	...	...	...	...	...	...	...	...	...	...	...
5.6	...	...	3.52	1.95	0.95	0.39	1.00	1.00	2.05	3.46	4.09	...	...	...	...	...	...	...	...	...	...
5.7	...	...	4.70	2.91	1.64	0.76	0.41	0.53	1.06	1.81	1.70	...	...	...	...	...	...	...	...	...	...
5.8	...	...	...	4.42	2.90	1.74	1.04	0.77	0.86	1.04	1.30	3.58	...	...	...	...	...	...	...	...	...
5.9	...	...	...	...	4.94	3.52	2.51	1.90	1.59	1.27	0.04	2.28	...	...	...	...	...	...	...	...	...
6.0	...	...	...	...	...	...	3.96	3.04	2.39	1.63	0.03	1.41	3.53	...	...	...	...	...	...	...	...
6.1	...	...	...	...	...	...	...	4.06	3.11	1.96	0.09	0.77	2.11	3.99	...	...	...	...	...	...	...
6.2	...	...	...	...	...	...	...	...	3.86	2.37	0.29	0.39	1.09	2.25	4.02	...	...	...	...	...	...
6.3	...	...	...	...	...	...	...	...	4.77	2.99	0.73	0.36	0.52	1.09	2.20	3.79	...	...	...	...	...
6.4	...	...	...	...	...	...	...	...	...	3.89	1.49	0.71	0.42	0.50	1.07	2.07	3.41	4.75	...	...	...
6.5	...	...	...	...	...	...	...	...	...	...	2.54	1.42	0.75	0.41	0.53	1.04	1.82	2.57	3.62	...	...
6.6	...	...	...	...	...	...	...	...	...	...	3.87	2.46	1.46	0.77	0.49	0.59	0.89	1.15	1.70	...	...
6.7	...	...	...	...	...	...	...	...	...	...	...	3.94	2.66	1.66	1.04	0.78	0.68	0.52	0.66	...	...
6.8	...	...	...	...	...	...	...	...	...	...	...	...	4.21	2.94	2.03	1.46	0.99	0.48	0.27	4.25	...
6.9	...	...	...	...	...	...	...	...	...	...	...	...	...	4.25	3.07	2.22	1.45	0.62	0.14	3.18	...
7.0	...	...	...	...	...	...	...	...	...	...	...	...	...	...	4.04	2.94	1.89	0.79	0.08	2.37	...
7.1	...	...	...	...	...	...	...	...	...	...	...	...	...	...	4.92	3.60	2.29	0.94	0.06	1.74	4.08
7.2	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	4.20	2.66	1.09	0.06	1.26	3.02
7.3	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	4.77	3.03	1.26	0.09	0.88	2.18
7.4	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	3.41	1.45	0.16	0.61	1.51
7.5	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	3.84	1.70	0.28	0.44	1.00
7.6	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	4.31	2.01	0.47	0.37	0.63
7.7	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	4.84	2.39	0.71	0.38	0.40
7.8	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	2.80	1.00	0.46	0.25
7.9	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	3.23	1.31	0.57	0.16
8.0	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	3.66	1.61	0.70	0.10

TABLE 5
 $\log_{10} N(z)/N_z$ FOR Ni IONS

$\log_{10} T_e$ (K)	Ni xi	Ni xii	Ni xiii	Ni xiv	Ni xv	Ni xvi	Ni xvii	Ni xviii	Ni xix	Ni xx	Ni xxi	Ni xxii	Ni xxiii	Ni xxiv	Ni xxv	Ni xxvi	Ni xxvii	Ni xxviii	Ni xxix
6.0	1.46	2.40	3.60	2.95	4.23	...	...	...	...	...	...	...	...	...	...	...	...	...	...
6.1	0.79	1.29	2.01	2.95	4.23	...	...	...	...	...	...	...	...	...	...	...	...	...	...
6.2	0.56	0.67	0.98	1.47	2.26	3.25	4.44	...	...	...	...	...	...	...	...	...	...	...	...
6.3	0.88	0.65	0.59	1.69	1.06	1.59	2.31	2.72	2.59	...	...	...	...	...	...	...	...	...	...
6.4	1.93	1.39	1.02	0.77	0.77	0.91	1.21	1.12	0.59	2.67	...	...	...	...	...	...	...	...	...
6.5	4.09	3.27	2.61	2.06	1.73	1.53	1.46	0.95	0.11	1.47	3.27	...	...	...	...	...	...	...	...
6.6	...	...	4.39	3.57	2.94	2.44	2.04	1.17	0.10	1.88	2.04	3.54	...	...	...	...	...	...	...
6.7	...	...	...	...	4.13	3.35	2.67	1.48	0.22	0.52	1.16	2.11	3.52	...	...	...	...	...	...
6.8	...	...	...	...	...	4.36	3.41	1.95	0.52	0.42	0.63	1.12	2.02	3.20	4.56	...	...	...	...
6.9	...	...	...	...	...	...	4.37	2.66	1.08	0.64	0.48	0.59	1.06	1.77	2.64	3.54	4.80	...	...
7.0	...	...	...	...	...	...	...	3.66	1.94	1.20	0.72	0.50	0.60	0.92	1.36	1.83	2.67	...	...
7.1	...	...	...	...	...	...	...	...	3.15	2.16	1.39	0.89	0.67	0.65	0.71	0.83	1.30	...	...
7.2	...	...	...	...	...	...	...	...	4.75	3.52	2.51	1.74	1.24	0.91	0.66	0.46	0.62	4.28	...
7.3	...	...	...	...	...	...	...	...	...	...	3.80	2.79	2.04	1.45	0.90	0.43	0.33	3.22	...
7.4	...	...	...	...	...	...	...	...	...	...	...	3.85	2.87	2.03	1.24	0.52	0.20	2.45	...
7.5	...	...	...	...	...	...	...	...	...	...	...	4.86	3.67	2.61	1.59	0.64	0.13	1.86	4.19
7.6	...	...	...	...	...	...	...	...	...	...	...	...	4.42	3.69	1.93	0.78	0.10	1.40	3.26
7.7	...	...	...	...	...	...	...	...	...	...	...	...	...	4.75	2.27	0.94	0.10	1.03	2.50
7.8	...	...	...	...	...	...	...	...	...	...	...	...	...	4.22	2.62	1.11	0.13	0.75	1.88
7.9	...	...	...	...	...	...	...	...	...	...	...	...	...	4.75	2.99	1.32	0.20	0.55	1.38
8.0	...	...	...	...	...	...	...	...	...	...	...	...	...	...	3.38	1.56	0.30	0.41	1.00
8.1	...	...	...	...	...	...	...	...	...	...	...	...	...	...	3.81	1.85	0.45	0.35	0.71
8.2	...	...	...	...	...	...	...	...	...	...	...	...	...	...	4.26	2.16	0.64	0.34	0.50
8.3	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	2.50	0.85	0.37	0.37
8.4	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	2.86	1.08	0.43	0.25
8.5	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	3.22	1.32	0.51	0.18

as a function of the local electron temperature by the corona ionization equilibrium relationships,

$$N_e N(z-1) S(z-1, g) = N_e N(z) \alpha(z, g), \quad 1 \leq z \leq Z, \quad (7)$$

together with the condition that the sum over all $N(z)$ corresponds to the total abundance N_Z . Here $N(z)$ denotes the number density of ions in the charge state z , which are assumed to be predominantly in the ground state configuration g , and N_e is the electron density. $S(z-1, g)$ denotes the combined rate coefficient for direct electron-impact ionization of $X^{+(z-1)}(g)$ (Lotz 1967) and for autoionization following inner-shell electron-impact excitation (Jordan 1969). The total recombination rate coefficient $\alpha(z, g)$ is the sum of the direct radiative recombination rate coefficient α_r (Jacobs *et al.* 1977a) and the total dielectronic recombination rate coefficient α_d which is tabulated in Tables 2 and 3. The interference terms between resonant and nonresonant contributions have been neglected.

It should be emphasized that the relative abundances $N(z)/N_Z$ of the ions which are obtained from the corona model are independent of density. Departures from the density independence can arise from several effects. First, the dielectronic recombination rate coefficient α_d can become density dependent as a result of the effects of collisions on the highly excited nl levels (Burgess and Summers 1969; Jacobs and Davis 1978). Provided that the electron density N_e is below 10^{14} cm^{-3} , these effects can be neglected for the highly charged ions which are most abundant in high-temperature plasmas. The occurrence of ionization and recombination processes from excited levels, e.g., metastables, can produce a density dependence; but the correct treatment of such processes requires a much more detailed calculation. Three-body recombination, which is included in our calculations, also produces a density dependence; but this process has never been found to be important in the low-density region of interest.

The relative abundances $N(z)/N_Z$ obtained for all of the ions of Ca are presented as functions of temperature in Table 4, while the results for Ni xi–Ni xxix are given in Table 5. The density dependence, which is not predicted by our calculations, is expected to be important for Ca i and Ca ii. The maximum equilibrium abundance temperatures which are given in Table 6 have their greatest significance for the ions with sharply peaked abundance curves. The inclusion of autoionization to excited states shifts the maximum abundance for most of the sharply peaked curves toward a lower temperature. For example, the characteristic temperature for Ni xx is predicted by our calculations to be $6.3 \times 10^6 \text{ K}$, whereas a temperature of $9.0 \times 10^6 \text{ K}$ is obtained from the results given by Jordan (1970). The shift in the abundance peaks due to autoionization into excited states becomes more important with increasing Z and has a significant effect on the ionization structure of Fe and Ni. This is due to

TABLE 6
MAXIMUM EQUILIBRIUM ABUNDANCE TEMPERATURES

Ion	T_e (K)	Ion	T_e (K)
Ca ii	1.0 (4) ^a	Ni xi	1.6 (6)
Ca iii	3.2 (4)	Ni xii	2.0 (6)
Ca iv	1.6 (5)	Ni xiii	2.2 (6)
Ca v	2.5 (5)	Ni xiv	2.3 (6)
Ca vi	3.2 (5)	Ni xv	2.5 (6)
Ca vii	4.0 (5)	Ni xvi	2.7 (6)
Ca viii	5.0 (5)	Ni xvii	3.0 (6)
Ca ix	6.3 (5)	Ni xviii	3.2 (6)
Ca x	8.0 (5)	Ni xix	4.0 (6)
Ca xi	1.0 (6)	Ni xx	6.3 (6)
Ca xii	2.0 (6)	Ni xxi	8.0 (6)
Ca xiii	2.5 (6)	Ni xxii	9.0 (6)
Ca xiv	3.2 (6)	Ni xxiii	1.0 (7)
Ca xv	4.0 (6)	Ni xxiv	1.3 (7)
Ca xvi	4.5 (6)	Ni xxv	1.6 (7)
Ca xvii	5.0 (6)	Ni xxvi	2.0 (7)
Ca xviii	6.3 (6)	Ni xxvii	5.0 (7)
Ca xix	1.3 (7)	Ni xxviii	1.6 (8)
Ca xx	4.0 (7)		

^a Numbers in parentheses are powers of 10.

the increasing importance of the affected $\Delta n_j \neq 0$ transitions in the dielectronic recombination process.

The mean charges $\langle z \rangle$ for Ca and Ni are shown as functions of temperature in Figure 1. The $\langle z \rangle$ curves are rapidly increasing functions of temperature in the region in which ions with sharply peaked abundance curves are predominant in the plasma. These curves become flat in the temperature region in which the Ne-like and He-like ions are predominant and also at the highest temperatures where all ions become completely

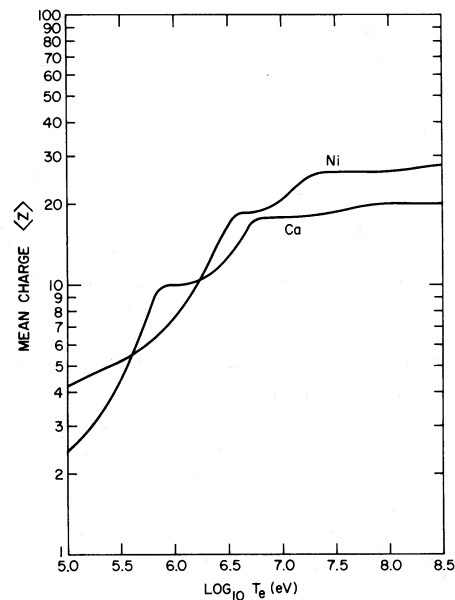


FIG. 1.—The mean charges for Ca and Ni ions in corona equilibrium.

stripped. The mean charges obtained with and without the inclusion of dielectronic recombination have been compared for Fe (Davis *et al.* 1977), and the inclusion of dielectronic recombination produces a substantial reduction in the temperature region where the ions with sharply peaked abundance curves are predominant. We note that a relatively small displacement of a sharply peaked abundance curve can have a significant effect on the spectral line intensity predicted at a given temperature.

IV. RADIATIVE EMISSION RATES

The power radiated per unit volume from the plasma as a result of electron-ion collisions may be expressed in the form

$$P_Z = N_e N_Z [\epsilon_Z^{(L)} + \epsilon_Z^{(D)} + \epsilon_Z^{(R)} + \epsilon_Z^{(B)}]. \quad (8)$$

The radiated power coefficients ϵ_Z , which have the dimensions of power $\times$ volume, are independent of density only in the corona model approximation.

Collisional excitation of resonance line radiation is expected to represent the dominant radiative energy-loss process for incompletely stripped ions in corona equilibrium. The radiated power coefficient $\epsilon_Z^{(L)}$ describing the electron-impact excitation of resonance line radiation is given by

$$\epsilon_Z^{(L)} = \sum_{z=1}^{Z-1} \frac{N(z)}{N_Z} \sum_j \Delta E(z, g \rightarrow j) \times C(z, g \rightarrow j) B(z, j \rightarrow g), \quad (9)$$

where $\Delta E(z, g \rightarrow j)$ are the excitation energies, $C(z, g \rightarrow j)$ are the electron impact excitation rate coefficients obtained from the distorted wave calculation, $B(z, j \rightarrow g)$ are the branching ratios for the radiative transitions in Table 1, and $N(z)/N_Z$ are the corona ionization equilibrium distributions in Tables 4 and 5. Reabsorption of the emitted radiation has been neglected.

Radiation is emitted close to the resonance lines of the recombining ion during the dielectronic recombination process. The radiated power coefficient $\epsilon_Z^{(D)}$ describing the dielectronic recombination satellite radiation due to the stabilizing transitions of the recombining ion is given by the expression which is obtained from equation (9) after replacing the products $C(z, g \rightarrow j) B(z, j \rightarrow g)$ by the dielectronic recombination rate coefficients associated with the transitions in Table 1. The additional contribution from stabilizing transitions of the recombining electron is found to be important only in the cases of the H-like and He-like ions, because for these ions the lowest possible n/l levels play the dominant role in Ca and Ni. In these cases the additional contribution is about 20% of the total dielectronic recombination contribution to the radiative emission rate. The radiation which is emitted when the recombined electron, which is most often in a highly excited state, cascades to the ground state has not been evaluated, because this contribution is expected

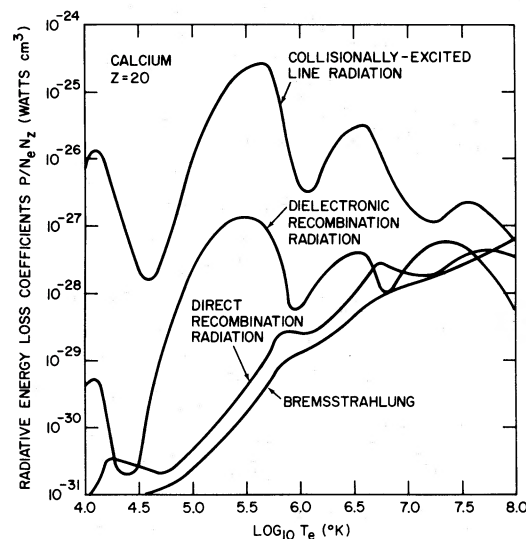


FIG. 2.—The radiative energy-loss rate coefficients for Ca ions in corona equilibrium.

to have a very strong density dependence. In the low-density limit, the cascade radiation may be more important than the radiation emitted in the stabilizing transitions.

The radiated power coefficients $\epsilon_Z^{(R)}$ and $\epsilon_Z^{(B)}$, which describe direct recombination radiation and electron-ion bremsstrahlung, respectively, were estimated by using simple expressions similar to those given by Griem (1964).

The radiative energy-loss rate coefficients for electron impact excitation of resonance line radiation, dielectronic recombination radiation, direct recombination radiation, and bremsstrahlung are shown as functions of temperature in Figures 2 and 3 for Ca and

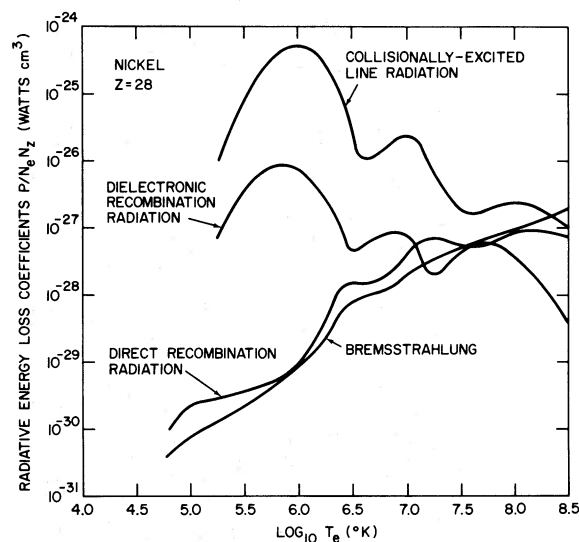


FIG. 3.—The radiative energy-loss rate coefficients for Ni ions in corona equilibrium.

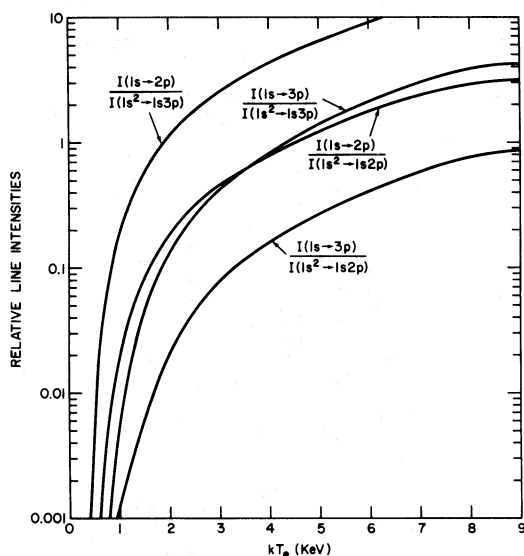


FIG. 4.—The ratios of the intensities of the $1s \rightarrow 2p$ and $1s \rightarrow 3p$ collisionally excited resonance lines from the H-like and He-like ions of Ca in corona equilibrium.

Ni, respectively. The resonance line and dielectronic recombination curves show broad peaks which correspond to the excitation of electrons from a given n shell. The K shell maximum is predominantly the result of the $1s \rightarrow 2p$ transitions in the He-like and H-like ions, whereas the L and M shell peaks are mainly the result of $\Delta n_i = 0$ transitions in a large number of lower adjacent ionization stages. Similar calculations were first reported by Cox and Tucker (1969), but the individual contributions to the total radiative energy-loss rate were not presented. Cooling rates for Ca and Ni have been reported by Raymond, Cox, and Smith (1976) which are somewhat larger (a factor of 5 in some cases) than our results. These differences are probably attributable to their use of the Gaunt factor approximation, which tends to overestimate the collision rates. It should be emphasized that our results are strictly applicable only to a low-density plasma in corona equilibrium. At higher densities, it is expected that the radiative emission coefficients will be reduced by the effects of collisional de-excitation competing with radiative decay and by reabsorption of the emitted radiation, although occasional enhancements may occur due to collisionally induced and photo-induced emissions. The radiation emitted following inner-shell excitation and ionization, which has not been evaluated in this investigation, is expected to become important for high- Z ions or in an ionizing plasma, where the electron temperature can greatly exceed the ionization equilibrium temperature. Dielectronic re-

combination radiation may be more important than line radiation in a recombining plasma, where the electron temperature can be far below the ionization equilibrium temperature.

The temperature sensitivity of the ratio of spectral line intensities arising from different stages of ionization z and z' is well known. In the corona model approximation the intensity ratio $I(z, j \rightarrow k)/I(z', j' \rightarrow k')$ is given by

$$\frac{I(z, j \rightarrow k)}{I(z', j' \rightarrow k')} = \frac{N(z)/N_z}{N(z')/N_{z'}} \frac{C(z, g \rightarrow j)B(z, j \rightarrow k)}{C(z', g' \rightarrow j')B(z', j' \rightarrow k')} \quad (10)$$

In Figure 4 the ratios of the intensities of the $1s \rightarrow 2p$ and $1s \rightarrow 3p$ collisionally excited resonance lines from the H-like and He-like ionization stages of Ca are shown as functions of temperature. The accuracy of the corona ionization equilibrium distributions obtained in this investigation is the primary justification for the presentation of these results. It should be noted that the unresolvable dielectronic recombination satellites, which have not been included in the calculation of these intensity ratios may make an important contribution to the observed line intensity.

V. CONCLUSIONS

We have carried out systematic calculations for the total dielectronic recombination rates of the ions of Ca and Ni in a low-density plasma, taking into account stabilizing radiative transitions of both the recombining electron and the recombining ion core. Stabilizing radiative transitions of the recombining ion are found, as expected, to be the most important stabilization processes for the ions which recombine predominantly through the dielectronic recombination process. The inclusion of dielectronic recombination shifts the corona ionization equilibrium abundance curves toward higher temperatures, but the Burgess formula can overestimate this shift for certain ions because of the neglect of autoionization to excited states and almost always overestimates α_d for $\Delta n \neq 0$ transitions of the recombining ion. The relative intensities of spectral lines and the total radiative emission rates at a given temperature can be substantially altered by the shift in the ionization-recombination structure.

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M. BLAHA: Department of Physics and Astronomy, University of Maryland, College Park, MD 20742

J. CAIN and M. DAVIS: Science Applications, Inc., 8400 Westpark Drive, McLean, VA 22101

J. DAVIS, V. L. JACOBS, and J. E. ROGERSON: Plasma Radiation Group, Code 6707, Plasma Physics Division, Naval Research Laboratory, Washington, DC 20375