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Calculation of Ionization Equilibria

For Oxygen, Neon, Silicon, and Iron

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John W. Allen and Andrea K. Dupree

Harvard College Observatory, Cambridge, Massachusetts

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CALCULATIONS OF IONIZATION EQUILIBRIA FOR OXYGEN, NEON, SILICON, AND IRON.

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I. INTRODUCTION

Calculations of the ionization equilibrium for a low density plasma must include processes that involve autoionizing atomic levels. Burgess (1965a) has noted the greater importance of dielectronic recombination than of radiative recombination. Goldberg et al. (1965) found that autoionization contributes to the total ionization rate for certain ions. We include both these processes in our calculations, and discuss their effect upon the maximum abundance of an ion and the temperature required for ion production.

Four elements are considered in detail: oxygen, neon, silicon, and iron. These elements produce some of the strongest coronal emission lines, and a consistent evaluation of their ionization equilibrium is necessary, especially for abundance determinations. The following processes are included: ionization by electron collision; excitation of autoionizing levels by electron collision; dielectronic recombination; radiative recombination.

II. EQUATIONS AND RATE COEFFICIENTS

At coronal temperatures and densities, an atom, X_j^{+m} may be ionized directly from level j by electron collision,

$$X_j^{+m} + e \rightarrow X_i^{+(m+1)} + e + e$$

or through the excitation of an intermediate level, X_d^{+m}, that subsequently autoionizes:

$$X_j^{+m} + e \rightarrow X_d^{+m} + e \rightarrow X_i^{+(m+1)} + e$$

Photoionization may also take place:

$$X_j^{+m} + h\nu \rightarrow X_i^{+(m+1)} + e$$

Recombination may occur directly, with the emission of a photon,

$$X_i^{+(m+1)} + e \rightarrow X_j^{+m} + h\nu$$

or by a radiationless recombination to a doubly excited level $X_{k,n\ell}^{+m}$, followed by a stabilizing transition to a bound level $X_{i,n\ell}^{+m}$, accompanied by the emission of a photon,

$$X_i^{+(m+1)} + e \rightarrow X_{k,n\ell}^{+m} \rightarrow X_{i,n\ell}^{+m} + h\nu(k\rightarrow i)$$

Three-body collisions are not important as a means of recombination in a low density plasma.

In the steady state, there is a balance between the number of ionizations and of recombinations. We denote the rate coefficients for ionization, autoionization, and photoionization (corrected for stimulated emission) by $q_{j,i}$, $q_{j,i}^a$, and $\alpha_{j,i}$ respectively. The dielectronic and radiative recombination coefficients are $\alpha_{i,j}^d$ and $\alpha_{i,j}^r$ respectively.

The equilibrium between two successive stages of ionization is expressed as:

$$\sum_{j=1}^{\infty} N_j^{+m}(N_e \cdot q_{j,i} + N_e \cdot q^a_{j,i} + \alpha_{j,i})$$

$$= N_i^{+(m+1)} \cdot N_e \cdot \sum_{j=1}^{\infty} (\alpha^d_{i,j} + \alpha^r_{i,j}) \tag{1}$$

We consider the population of the j-th level of X^{+m} to be determined by the balance between recombinations and cascade into the level and spontaneous transitions and ionization out of the level:

$$N_j^{+m}\left[\sum_{k<j} A_{j,k} + N_e(q_{j,i} + q^a_{j,i}) + \alpha_{j,i}\right]$$
$$= N_i^{+(m+1)} \cdot N_e(\alpha^d_{i,j} + \alpha^r_{i,j}) + \sum_{k>j} N_k^{+m} A_{k,j} \; . \tag{2}$$

Substituting Eq. (2) for the population of the excited levels N_j^{+m} into Eq. (1), we find

$$N_1^{+m}(q_{1,i} + q^a_{1,i}) \tag{3}$$
$$= N_i^{+(m+1)}\left\{\alpha^d_{i,1} + \alpha^r_{i,1} + \sum_{j=2}^{\infty}\left[\alpha^d_{i,j} + \alpha^r_{i,j}\right] \cdot \left[1/\left(1 + \frac{N_e(q_{j,i} + q^a_{j,i}) + \alpha_{j,i})}{\sum_{k<j} A_{j,k}}\right]\right\}$$

In the solar corona, photoionization from the ground state is not possible, therefore $\alpha_{1,i}$ is omitted. The contribution of cascades to the population of excited levels is also ignored. In this general case, the ionization equilibrium depends on both the electron density and the radiation field. This dependence arises because the population of high levels may be decreased by collisional or photo-ionization. Eq. (3) is written so that ionization processes from a given level, if more frequent than spontaneous transitions, reduce the recombination rate to that level. Although this affects levels close to the ionization limit, it can be significant for dielectronic recombination in which electrons are captured primarily into these high levels. Sunyaev and

Vainshtein (1967) first noted the influence of photoionization upon the effective recombination rate. However, we find electron collisions to be the predominant method of ionization. If the total recombination rate is reduced, the equilibrium curves will be shifted to lower temperatures.

At present we restrict our calculations to low particle and radiation densities ensuring that spontaneous transitions will be very much more frequent than ionizing transitions:

$$\sum_{k<j} A_{j,k} >> N_e(q_{j,i}+q^a_{j,i}) + \alpha_{j,i}$$

and we obtain

$$N_1^{+m}(q_{1,i}+q^a_{1,i}) = N_i^{+(m+1)} \cdot \sum_{j=1}^{\infty}(\alpha^d_{i,j}+\alpha^r_{i,j}) \qquad (4)$$

This equation is independent of electron density, and is representative of the set of equations that we solved to determine the ionization equilibrium. For certain of the ions, however, the applicability of Eq. (4) is restricted to conditions much different from those found in the solar corona, for instance. This is discussed further in Section IV.

The collisional ionization rate coefficient is taken from Seaton (1964b):

$$q_{j,i} = 2.0\text{x}10^{-8} \cdot T^{\frac{1}{2}} \cdot \sum_{n\ell} \frac{\zeta_m(n\ell)\, 10^{-5040\; I_m(n\ell)/T}}{I_m^2(n\ell)} \qquad (5)$$

where $\zeta_m(n\ell)$ is the number of electrons having principal quantum number n and angular quantum number ℓ and I_m is the ionization potential (eV) of a $(n\ell)$ electron. Ionization of the valence electron as well as inner shell electrons was included.

To obtain the autoionization rate, we used the collisional excitation rate of Seaton (1964b):

$$q_{j,k}=1.70 \times 10^{-3} \cdot \frac{f_{jk}}{W_{jk}} \cdot \frac{10^{-5040 W_{jk}/kT}}{T^{\frac{1}{2}}} P(W_{jk}/kT) \quad (\mathrm{cm^3 sec^{-1}}) \qquad (6)$$

Here f_{jk} is the absorption oscillator strength of the autoionizing transition, W_{jk} (eV) is the energy of the transition; the function $P(W_{jk}/kT)$ has been tabulated by van Regemorter (1962). Only collisions from the ground state were considered. The total autoionization rate is found by a summation over all upper levels k that lie above the first ionization limit and are able to autoionize,

$$q^a_{j,i} = \sum_k q_{j,k} \; .$$

The selection rules governing autoionization are discussed by Condon and Shortley (1935). Our methods for obtaining energy levels and oscillator strengths for transitions to autoionizing levels are treated below.

The radiative recombination rate to all levels of an ion X^{+m},

$$\alpha^r_{tot} = \sum_{j=1}^{\infty} \alpha^r_{i,j}$$

is adopted from Seaton's (1959) hydrogenic approximation:

$$\alpha^r_{tot} = 5.20 \times 10^{-14} (m+1) \lambda^{\frac{1}{2}} \cdot \{0.43 + \tfrac{1}{2}\ln \lambda + 0.47\lambda^{-\frac{1}{3}}\} \; (\mathrm{cm^3 sec^{-1}}) \qquad (7)$$

where $\lambda = 157890 \cdot (m+1)^2/T.$

The total dielectronic recombination coefficient to an ion X^{+m},

$$\alpha^d_{tot} = \sum_{j=1}^{\infty} \alpha^d_{i,j}$$

has been derived by Burgess (1965a) as:

$$\alpha^{d}_{tot} = 3.03 \cdot 10^{-3} \; T^{-3/2} \; B(m+1) \tag{8}$$
$$\cdot \sum_k f_{ik} \; A(x) \cdot \exp - \left[1.44 E_{ik} / T \left(1 + \frac{.015 (m+1)^3}{(m+2)^2}\right) \right].$$

In this equation,

$$B(m+1) = (m+1)^{\frac{1}{2}} \; (m+2)^{5/2} \left[(m+1)^2 + 13.4 \right]^{-\frac{1}{2}}$$

$$A(x) = x^{\frac{1}{2}} / (1 + 0.105 \; x + 0.015 x^2)$$

and $\quad x = 9.113 \cdot 10^{-6} \; E_{ik} / (m+2).$

The summation in Eq.(8) is over those excited levels, $X_k^{+(m+1)}$ from which radiative transitions to the ground level, $X_i^{+(m+1)}$ are possible. f_{ik} is the absorption oscillator strength and $E_{ik}(cm^{-1})$ is the energy of the transition.

III. THE CALCULATIONS

A FORTRAN II code has been written to evaluate the rate coefficients and to solve the set of coupled equations given by Eq. (4). A listing of this code is available upon request.

The calculations require a large amount of atomic data which were assembled from a variety of sources. Ionization energies were taken from Moore (1949,1952) if available, otherwise the values tabulated by Allen (1963) were used. Term energies and oscillator strengths of transitions to the ground level are necessary to evaluate both the dielectronic recombination and autoionization rates. Experimental energy values were used whenever available. In many cases, particularly for non-resonance transitions and autoionizing levels, term energies were calculated by a Hartree-Fock SCF computer code written by Froese (1964a) or by the quantum-defect method. With the latter procedure, energies of the lowest term in the series, if not experimentally determined, were obtained from the Hartree-Fock program of Froese (1964a). These calculations require values of the Slater coefficients for term energies as input data. These data have been tabulated only for selected configurations (Slater 1960). Recoupling calculations were carried out for certain terms of O IV, Si II, and Si X. For most autoionizing levels in silicon it was necessary to approximate the energy by that of the term of highest multiplicity. Energy corrections to allow for a lower multiplicity parent were introduced by assuming the final term separation to be equal to that of their respective series limits.

Values of oscillator strengths were taken from the literature when possible, but for a majority of the transitions, it was necessary to make our own calculations. Only transitions allowed under L-S coupling were considered. In all cases, we derived the oscillator strength for the series of transitions from the ground term, up to and including levels with principal quantum number, $n = 6$. In a few instances where energies were available, the series extended to $n = 8$ or 9. For the four elements considered, calculation of the dielectronic rate required more than one thousand f-values and the autoionizing transitions increased this number by 10%.

Several standard methods were used to obtain the necessary transition integrals. In about one-half of the cases they were calculated by using the Froese (1964a) Hartree-Fock program. The remainder were obtained by using Coulomb wave functions from a computer program written by Lewis (1967), or the Bates-Damgaard tables (1949) or from the hydrogenic integrals tabulated by Green et al. (1957). The Shore and Menzel (1965) tables provided the line and multiplet factors in L-S coupling. Configuration interaction was not considered in our calculated f-values; however, many of the values taken from the literature do include these effects. A listing of additional sources of data for each element follows:

<u>Oxygen</u>

O I: Huffman, Larrabee, and Tanaka (1967), Energies of autoionizing levels.

O II: Kelly (1964), Transition integrals and energy levels (n=6 to 8). These energy values were increased by an amount determined from a comparison of lower series values with experiment. Cohen and Dalgarno (1964).

O III: Kelly (1964), Transition integrals and energy levels (n=5 to 8). See comments for O II.

O IV: Kelly (1964), Transition integrals and energy levels (n=6 to 8). Hartree-Fock energies calculated with the Froese (1964a) FORTRAN II code were adjusted as were the Kelly (1964) energies for O II - IV. Cohen and Dalgarno (1964).

O V: Kelly (1964), Transition integrals.

Cohen and Dalgarno (1964).

O VI: Kelly (1964), Transition integrals.

O VIII: Adjusted Hartree-Fock energies, (see O IV).

Neon

All stages: Wiese et al. (1966).

Silicon

Si II: Froese and Underhill (1966); Moore (1965).

Si III: Crossley and Dalgarno (1965).

Iron

Fe VI, VII: Hydrogenic energies and f-sum rule invoked for oscillator strength of autoionizing transitions of lowest energy.

Fe VIII: Cowan and Peacock (1966); Czyzak and Krueger (1966).

Fe IX: Froese (1967).

Fe X, XI: Froese (1967); Varsavsky (1962).

Fe XIV: Garstang (1962).

Fe XV, XVI: Froese (1964b).

Fe XVII: Garstang (1966).

The compilation of energy levels and oscillator strengths is too lengthy to be given here, but is available upon request.

IV. DISCUSSION

The results of our calculations for the elements oxygen, neon, silicon, and iron are tabulated in Tables 1 - 7 where values of the quantity $-\log_{10}(N^{+m}/N_{tot})$ are given as a function of temperature. These data are also presented in Figures 1 - 4.

The effects of dielectronic recombination upon the ionization equilibrium are several. The temperature of maximum abundance of an ion is increased, and the maximum value of the concentration of an ion may also change. The curve of fractional concentration for a given ion is no longer sharply peaked, indicating that the ion is present over a larger range of temperature than when dielectronic recombination is not included. These effects are presented for each ion in Table 8. Here we have tabulated for each ion the temperature at maximum abundance, the maximum fractional concentration, and the temperatures at which each curve decreases to one third of its maximum value. There seems to be no systematic variation in any quantity along an isoelectronic sequence. The shift of the maximum to higher temperatures appears to be larger for heavier elements (iron) than for the lighter elements. But the lack of any systematic behavior indicates that calculations involving detailed evaluation of the dielectronic rate are necessary for each ion in order to determine the ionization equilibrium.

The inclusion of collisional excitation to autoionizing levels increases the effective ionization rate at a given temperature. Only if this increase occurs near maximum concentration of an ion will it have a significant effect on the ionization equilibrium. The preliminary results of Goldberg, Dupree, and Allen (1965) for both oxygen and iron are confirmed. The concentrations of oxygen and silicon change little when autoionization is included. Therefore, we did not consider this process in the calculations for neon. Certain iron ions show the effects of an increased ionization rate: the maximum is displaced again to lower temperatures (0.02 - 0.15 dex). The concentration curve is narrowed for some ions (Fe XIV, XV, XVI), whereas for others (Fe IX, XVII) the curves are broadened. These effects for iron are discussed in greater detail elsewhere (Dupree 1967). It is apparent that the process of autoionization can not be ignored in the ionization equilibrium of certain elements.

The calculations discussed above are for conditions of low particle and radiation density, and include collisional ionization processes from the ground level only. For specific ions, we now evaluate the rate of ionization from upper levels by electron collisions and absorption of radiation, In this way we can obtain an approximate estimate of the regimes for which our assumptions are expected to be valid.

In order for the ionization equilibrium to change, the factor

$$1 + \left[N_e(q_{j,i} + q^a_{j,i}) + \alpha_{j,i} \right] / \sum_{k<j} A_{j,k} \qquad (9)$$

must be significantly greater than one when $j \leqslant 150$. At approximately this value of the principal quantum number, 80% of the total dielectronic recombination rate has been attained by the summation in Eq.(3), (Burgess 1965b).

In the solar corona with typical electron densities of 10^7 -10^{10} cm^{-3}, we find that the rate of photoionization by photospheric radiation is less than that of ionization by electron impact. Therefore, at present photoionization is ignored. Using a hydrogenic approximation (Seaton 1964a), we next determine the principal quantum number, j_o, at which the collisional ionization rate equals the rate of spontaneous transitions from level j. This value is given by:

$$\log j_o \cong 2.22 - \frac{1}{7} \log N_e + \frac{6}{7} \log Z + \frac{1}{14} \log T \qquad (10)$$

If $j_o < 150$, the total recombination rate will be significantly reduced in the formulation of Eq. (3). For many of the ions, however, $j_o \gtrsim 150$, and the recombination rate is not greatly changed. A density-independent ionization equilibrium should be satisfactory. We list these ions in Table 9. It is seen that for most of the heavy ions or for those occurring at high temperatures, it is not necessary to consider effects of increased density. A density dependent solution of the ionization equilibrium which is applicable to the chromosphere and corona is being developed.

In other astrophysical plasmas of low density such as H II regions ($N_e \approx 10^4$ cm^{-3}) or a galactic corona ($N_e \approx 10^{-2}$ cm^{-3}), ionization from high levels, either by collisions or by the 3° blackbody background radiation does not predominate over spontaneous transitions as has been suggested (Sunyaev and Vainshtein 1967). Hence when ionization is by electron impact from the ground state, a density independent solution appears to be adequate.

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TABLE 1

OXYGEN RELATIVE ION POPULATIONS*: $-\log\left(N(O^{+m})/N_{tot}\right)$

Stage of Ionization (m+1)

log T	I	II	III	IV	V	VI	VII	VIII
4.00	0.01	1.85						
4.05	0.04	1.07						
4.10	0.17	0.48						
4.15	0.50	0.16						
4.20	0.97	0.05						
4.25	1.43	0.02						
4.30	1.83	0.01						
4.35	2.13	0.003						
4.40	2.35	0.002						
4.45	2.50	0.002	2.70					
4.50	2.62	0.004	2.11					
4.55	2.72	0.01	1.61					
4.60	2.83	0.03	1.19					
4.65	2.94	0.07	0.84					
4.70		0.14	0.56					
4.75		0.26	0.35					
4.80		0.41	0.22	2.40				
4.85		0.60	0.13	1.90				
4.90		0.80	0.094	1.47				
4.95		1.01	0.085	1.11				
5.00		1.23	0.106	0.80				
5.05		1.46	0.16	0.57	2.61			
5.10		1.72	0.25	0.39	2.03			
5.15		2.00	0.38	0.27	1.54			
5.20		2.29	0.53	0.201	1.14			
5.25		2.62	0.72	0.185	0.82	2.63		
5.30		2.96	0.94	0.218	0.57	1.98		
5.35			1.20	0.30	0.400	1.45	2.40	
5.40			1.51	0.45	0.310	1.03	1.58	
5.45			1.88	0.67	0.321	0.744	0.94	
5.50			2.37	1.02	0.47	0.626	0.49	
5.55			2.98	1.49	0.76	0.674	0.24	
5.60				2.03	1.13	0.83	0.12	
5.65				2.58	1.52	1.02	0.06	
5.70					1.91	1.23	0.03	
5.75					2.28	1.42	0.02	
5.80					2.63	1.61	0.01	
5.85					2.95	1.79	0.008	
5.90						1.94	0.006	
5.95						2.08	0.005	2.63

*The processes included are collisional ionization, radiative recombination and dielectronic recombination.

TABLE 1 (Continued)

OXYGEN RELATIVE ION POPULATIONS*

	Stage of Ionization (m+1)			
log T	VI	VII	VIII	IX
6.00	2.19	0.006	2.12	
6.05	2.28	0.01	1.68	
6.10	2.35	0.03	1.30	
6.15	2.41	0.05	0.98	2.86
6.20	2.47	0.10	0.73	2.21
6.25	2.55	0.16	0.54	1.66
6.30	2.66	0.26	0.42	1.20
6.35	2.80	0.39	0.354	0.83
6.40	2.99	0.56	0.352	0.55
6.45		0.78	0.409	0.36
6.50		1.03	0.51	0.22
6.55		1.30	0.65	0.14
6.60		1.58	0.79	0.09
6.65		1.86	0.95	0.06
6.70		2.13	1.10	0.04
6.75		2.40	1.25	0.03
6.80		2.66	1.40	0.02
6.85		2.91	1.53	0.01
6.90			1.67	0.01
6.95			1.79	0.01
7.00			1.91	0.01
7.05			2.03	0.00
7.10			2.14	0.00
7.15			2.25	0.00
7.20			2.35	0.00
7.25			2.45	0.00
7.30			2.55	0.00
7.35			2.65	0.00
7.40			2.74	0.00
7.45			2.83	0.00
7.50			2.93	0.00

*See footnote on preceding page.

TABLE 2

OXYGEN RELATIVE ION POPULATIONS:* $-\log\left(N(O^{+m})/N_{tot}\right)$

Stage of Ionization (m+1)

log T	I	II	III	IV	V	VI	VII	VIII
4.00	0.01	1.84						
4.05	0.04	1.07						
4.10	0.18	0.48						
4.15	0.51	0.16						
4.20	0.98	0.05						
4.25	1.45	0.02						
4.30	1.85	0.01						
4.35	2.15	0.003						
4.40	2.37	0.002						
4.45	2.53	0.002	2.67					
4.50	2.65	0.005	2.08					
4.55	2.75	0.01	1.58					
4.60	2.86	0.03	1.16					
4.65	2.98	0.07	0.81					
4.70		0.15	0.53					
4.75		0.27	0.34	2.97				
4.80		0.43	0.21	2.37				
4.85		0.62	0.13	1.87				
4.90		0.82	0.091	1.44				
4.95		1.03	0.084	1.08				
5.00		1.25	0.108	0.79				
5.05		1.49	0.17	0.55	2.52			
5.10		1.74	0.26	0.38	1.95			
5.15		2.02	0.39	0.26	1.48			
5.20		2.32	0.55	0.201	1.09			
5.25		2.65	0.74	0.190	0.78	2.59		
5.30		3.00	0.97	0.229	0.54	1.95		
5.35			1.23	0.32	0.378	1.43	2.38	
5.40			1.54	0.47	0.296	1.02	1.57	
5.45			1.92	0.69	0.314	0.737	0.93	
5.50			2.40	1.04	0.47	0.624	0.49	
5.55				1.51	0.76	0.673	0.24	
5.60				2.05	1.13	0.83	0.12	
5.65				2.60	1.52	1.02	0.06	
5.70					1.91	1.23	0.03	
5.75					2.28	1.42	0.02	
5.80					2.63	1.61	0.01	
5.85					2.95	1.79	0.008	
5.90						1.94	0.006	
5.95						2.08	0.005	2.63

*The processes included are collisional ionization, collisional excitation of autoionizing levels, radiative recombination and dielectronic recombination. For higher temperatures, the relative ion populations are the same as those given in Table 1.

TABLE 3

NEON RELATIVE ION POPULATIONS*: $-\log\left(N(Ne^{+m})/N_{tot}\right)$

Stage of Ionization (m+1)

log T	I	II	III	IV	V	VI
4.10	0.000					
4.15	0.001	2.71				
4.20	0.007	1.82				
4.25	0.041	1.05				
4.30	0.18	0.46				
4.35	0.53	0.15				
4.40	1.01	0.045				
4.45	1.50	0.014				
4.50	1.96	0.006	2.54			
4.55	2.34	0.009	1.80			
4.60	2.66	0.030	1.19			
4.65	2.93	0.092	0.72			
4.70		0.22	0.41			
4.75		0.40	0.22			
4.80		0.61	0.12	2.49		
4.85		0.82	0.076	1.96		
4.90		1.04	0.057	1.50		
4.95		1.25	0.063	1.11		
5.00		1.46	0.096	0.79		
5.05		1.70	0.17	0.53	2.96	
5.10		1.95	0.28	0.34	2.31	
5.15		2.24	0.43	0.22	1.77	
5.20		2.54	0.61	0.15	1.32	
5.25		2.86	0.81	0.13	0.96	
5.30			1.04	0.16	0.68	2.51
5.35			1.29	0.22	0.47	1.92
5.40			1.57	0.33	0.33	1.44
5.45			1.87	0.48	0.25	1.05
5.50			2.19	0.66	0.23	0.75
5.55			2.55	0.88	0.26	0.53
5.60			2.93	1.13	0.34	0.38
5.65				1.42	0.46	0.29
5.70				1.75	0.64	0.28
5.75				2.13	0.88	0.34
5.80				2.61	1.23	0.52
5.85					1.71	0.84
5.90					2.30	1.28
5.95					2.93	1.78
6.00						2.28
6.05						2.76

*The processes included are collisional ionization, radiative recombination, and dielectronic recombination.

TABLE 3 (Continued)

NEON RELATIVE ION POPULATIONS*

Stage of Ionization (m+1)

log T	VII	VIII	IX	X	XI
5.50	2.41				
5.55	1.84				
5.60	1.38	2.79			
5.65	1.01	2.09			
5.70	0.74	1.51	2.12		
5.75	0.56	1.07	1.35		
5.80	0.52	0.78	0.77		
5.85	0.64	0.68	0.40		
5.90	0.89	0.73	0.20		
5.95	1.20	0.86	0.11		
6.00	1.54	1.02	0.060		
6.05	1.86	1.19	0.037		
6.10	2.18	1.34	0.023		
6.15	2.47	1.49	0.016		
6.20	2.73	1.62	0.012	2.64	
6.25	2.98	1.73	0.012	2.18	
6.30		1.82	0.015	1.77	
6.35		1.89	0.023	1.42	
6.40		1.96	0.040	1.12	2.93
6.45		2.03	0.070	0.87	2.32
6.50		2.11	0.12	0.67	1.80
6.55		2.22	0.19	0.52	1.35
6.60		2.35	0.28	0.43	0.98
6.65		2.52	0.42	0.39	0.69
6.70		2.73	0.59	0.40	0.47
6.75		2.98	0.80	0.45	0.31
6.80			1.04	0.55	0.21
6.85			1.29	0.66	0.14
6.90			1.54	0.79	0.092
6.95			1.80	0.92	0.063
7.00			2.05	1.05	0.045
7.05			2.30	1.18	0.032
7.10			2.54	1.31	0.023
7.15			2.78	1.43	0.017
7.20				1.55	0.013

*See footnote on preceding page.

TABLE 3 (Continued)

NEON RELATIVE ION POPULATIONS*

Stage of Ionization (m+1)

log T	X	XI
7.25	1.66	0.010
7.30	1.77	0.008
7.35	1.88	0.006
7.40	1.98	0.005
7.45	2.08	0.004
7.50	2.18	0.003
7.55	2.27	0.002
7.60	2.37	0.002
7.65	2.46	0.002
7.70	2.55	0.001
7.75	2.64	0.001
7.80	2.73	0.001
7.85	2.82	0.001
7.90	2.91	0.001
7.95	2.99	0.000

*See footnote on first page of this table.

TABLE 4

SILICON RELATIVE ION POPULATIONS*: $-\log\left(N(Si^{+m})/N_{tot}\right)$

Stage of Ionization (m+1)

log T	I	II	III	IV	V	VI	VII	VIII
4.00	1.03	0.04						
4.05	1.40	0.02						
4.10	1.67	0.010						
4.15	1.84	0.008	2.41					
4.20	1.96	0.010	1.93					
4.25	2.05	0.02	1.54					
4.30	2.13	0.03	1.22					
4.35	2.22	0.06	0.95					
4.40	2.33	0.09	0.72					
4.45	2.46	0.15	0.53					
4.50	2.62	0.24	0.38					
4.55	2.80	0.34	0.27					
4.60		0.47	0.18	2.63				
4.65		0.61	0.13	2.13				
4.70		0.77	0.092	1.69				
4.75		0.94	0.080	1.31	2.52			
4.80		1.13	0.096	0.98	1.70			
4.85		1.37	0.17	0.742	1.00			
4.90		1.72	0.36	0.643	0.50			
4.95		2.23	0.72	0.728	0.21			
5.00		2.85	1.18	0.94	0.09			
5.05			1.67	1.20	0.04			
5.10			2.15	1.45	0.02			
5.15			2.59	1.69	0.01			
5.20			2.99	1.89	0.007	2.90		
5.25				2.05	0.006	2.34		
5.30				2.16	0.009	1.85		
5.35				2.23	0.02	1.42		
5.40				2.28	0.04	1.06		
5.45				2.33	0.08	0.77		
5.50				2.39	0.15	0.54	2.40	
5.55				2.48	0.25	0.38	1.86	
5.60				2.59	0.37	0.28	1.42	
5.65				2.74	0.51	0.223	1.06	2.43
5.70				2.92	0.68	0.217	0.78	1.82
5.75					0.89	0.260	0.57	1.32
5.80					1.13	0.36	0.443	0.94
5.85					1.43	0.52	0.398	0.66
5.90					1.79	0.74	0.434	0.491
5.95					2.20	1.03	0.54	0.413
6.00					2.66	1.36	0.72	0.415
6.05						1.74	0.95	0.49
6.10						2.17	1.23	0.62
6.15						2.65	1.57	0.82
6.20							1.97	1.08
6.25							2.45	1.43
6.30								1.87
6.35								2.41

*The processes included are collisional ionization, radiative recombination and dielectronic recombination.

TABLE 4 Continued

SILICON RELATIVE ION POPULATIONS*
Stage of Ionization (m+1)

log T	V	VI	VII	VIII	IX	X	XI	XII	XIII
5.85	1.43	0.52	0.398	0.66	1.38	2.95			
5.90	1.79	0.74	0.434	0.491	0.98	2.23			
5.95	2.20	1.03	0.54	0.413	0.69	1.66			
6.00	2.66	1.36	0.72	0.415	0.50	1.22	2.46		
6.05		1.74	0.95	0.49	0.403	0.88	1.86		
6.10		2.17	1.23	0.62	0.376	0.64	1.39	2.41	
6.15		2.65	1.57	0.82	0.422	0.488	1.02	1.80	2.43
6.20			1.97	1.08	0.54	0.426	0.75	1.32	1.68
6.25			2.45	1.43	0.75	0.463	0.606	0.97	1.09
6.30				1.87	1.06	0.61	0.582	0.761	0.66
6.35				2.41	1.47	0.87	0.681	0.687	0.38
6.40					1.96	1.21	0.87	0.713	0.22
6.45					2.48	1.59	1.10	0.79	0.14
6.50					3.00	1.98	1.35	0.90	0.09

*See footnote on preceding page.

TABLE 4 Continued

SILICON RELATIVE ION POPULATIONS*

Stage of Ionization (m+1)

log T	X	XI	XII	XIII	XIV	XV
6.55	2.36	1.60	1.01	0.06	2.93	
6.60	2.72	1.83	1.11	0.05	2.48	
6.65		2.05	1.20	0.037	2.09	
6.70		2.25	1.28	0.034	1.75	
6.75		2.44	1.36	0.038	1.45	
6.80		2.63	1.44	0.05	1.19	2.85
6.85		2.81	1.52	0.07	0.97	2.33
6.90		3.00	1.60	0.10	0.78	1.87
6.95			1.71	0.15	0.63	1.47
7.00			1.84	0.22	0.51	1.13
7.05			1.99	0.32	0.437	0.85
7.10			2.18	0.45	0.405	0.62
7.15			2.40	0.60	0.413	0.45
7.20			2.65	0.79	0.45	0.32
7.25			2.92	0.99	0.52	0.23
7.30				1.20	0.61	0.16
7.35				1.43	0.70	0.12
7.40				1.65	0.81	0.09
7.45				1.87	0.91	0.06
7.50				2.09	1.02	0.05
7.55				2.31	1.12	0.04
7.60				2.52	1.22	0.03
7.65				2.73	1.32	0.02
7.70				2.93	1.42	0.02
7.75					1.52	0.01
7.80					1.62	0.01
7.85					1.71	0.01
7.90					1.80	0.01
7.95					1.89	0.01
8.00					1.98	0.01

*See footnote on first page of this table.

TABLE 5

SILICON RELATIVE ION POPULATIONS*: $-\log\left(N(Si^{+m})/N_{tot}\right)$

Stage of Ionization (m+1)

log T	I	II	III	IV	V	VI	VII	VIII	IX
4.00	1.03	0.04							
4.05	1.40	0.02							
4.10	1.67	0.010	2.90						
4.15	1.84	0.009	2.28						
4.20	1.96	0.012	1.80						
4.25	2.05	0.02	1.41						
4.30	2.14	0.04	1.10						
4.35	2.24	0.07	0.84						
4.40	2.36	0.12	0.63						
4.45	2.50	0.19	0.45						
4.50	2.66	0.28	0.32						
4.55	2.85	0.40	0.22						
4.60		0.53	0.15	2.60					
4.65		0.68	0.11	2.11					
4.70		0.83	0.080	1.68					
4.75		1.00	0.072	1.30	2.52				
4.80		1.19	0.092	0.98	1.69				
4.85		1.43	0.17	0.739	1.00				
4.90		1.78	0.36	0.642	0.50				
4.95		2.28	0.72	0.728	0.21				
5.00		2.89	1.18	0.94	0.09				
5.05			1.68	1.20	0.04				
5.10			2.15	1.46	0.02				
5.15			2.60	1.69	0.010				
5.20			2.99	1.90	0.007	2.73			
5.25				2.06	0.007	2.19			
5.30				2.18	0.012	1.71			
5.35				2.26	0.03	1.31			
5.40				2.32	0.05	0.96			
5.45				2.39	0.10	0.69	2.91		

*The processes included are collisional ionization, collisional excitation of autoionizing levels, radiative recombination and dielectronic recombination.

TABLE 5 Continued

SILICON RELATIVE ION POPULATIONS*

Stage of Ionization (m+1)

log T	IV	V	VI	VII	VIII	IX	X	XI	XII	XIII
5.50	2.47	0.18	0.48	2.29						
5.55	2.58	0.28	0.34	1.78						
5.60	2.72	0.41	0.249	1.35						
5.65	2.88	0.56	0.208	1.01	2.35					
5.70		0.74	0.212	0.74	1.76					
5.75		0.94	0.27	0.54	1.27	2.54				
5.80		1.20	0.37	0.429	0.90	1.87				
5.85		1.50	0.54	0.394	0.64	1.35	2.90			
5.90		1.86	0.77	0.438	0.476	0.95	2.20			
5.95		2.27	1.06	0.55	0.406	0.68	1.63			
6.00		2.72	1.40	0.73	0.413	0.50	1.20	2.44		
6.05			1.78	0.96	0.49	0.400	0.87	1.85		
6.10			2.21	1.25	0.63	0.377	0.63	1.37	2.39	
6.15			2.68	1.59	0.83	0.425	0.483	1.01	1.79	2.42
6.20				1.99	1.09	0.55	0.424	0.75	1.31	1.68
6.25				2.47	1.44	0.76	0.462	0.603	0.97	1.09
6.30					1.88	1.07	0.61	0.581	0.759	0.66
6.35					2.42	1.48	0.87	0.681	0.686	0.38
6.40						1.96	1.22	0.87	0.713	0.22
6.45						2.48	1.60	1.11	0.80	0.14
6.50						3.00	1.99	1.36	0.90	0.09

*See footnote on preceding page.

TABLE 5 Continued

SILICON RELATIVE ION POPULATIONS*

	Stage of Ionization (m+1)					
Log T	X	XI	XII	XIII	XIV	XV
6.55	2.37	1.60	1.01	0.06	2.93	
6.60	2.73	1.84	1.11	0.04	2.48	
6.65		2.06	1.21	0.036	2.09	
6.70		2.26	1.29	0.034	1.75	
6.75		2.46	1.37	0.037	1.45	
6.80		2.65	1.45	0.05	1.19	2.85
6.85		2.83	1.53	0.07	0.96	2.33
6.90			1.62	0.10	0.78	1.87
6.95			1.73	0.15	0.62	1.47
7.00			1.86	0.22	0.51	1.13
7.05			2.01	0.32	0.437	0.85
7.10			2.20	0.44	0.405	0.62
7.15			2.42	0.60	0.413	0.44
7.20			2.67	0.79	0.45	0.32
7.25			2.94	0.99	0.52	0.23

*See footnote on first page of this table. For higher temperatures, the relative ion populations are the same as those given in Table 4.

TABLE 6

IRON RELATIVE ION POPULATIONS*: $-\log\ N(Fe^{+m})/N_{tot}$

Stage of Ionization (m+1)

log T	VII	VIII	IX	X	XI	XII	XIII
5.00	2.96						
5.05	2.47						
5.10	2.07						
5.15	1.73						
5.20	1.44						
5.25	1.20						
5.30	0.98						
5.35	0.80	2.84					
5.40	0.65	2.42					
5.45	0.51	2.04					
5.50	0.41	1.71					
5.55	0.32	1.41					
5.60	0.27	1.14	2.80				
5.65	0.24	0.91	2.34				
5.70	0.23	0.72	1.92				
5.75	0.26	0.56	1.56				
5.80	0.31	0.45	1.24	2.46			
5.85	0.40	0.37	0.97	1.94			
5.90	0.53	0.33	0.76	1.50	2.54		
5.95	0.70	0.35	0.60	1.12	1.93	2.93	
6.00	0.93	0.43	0.51	0.83	1.42	2.19	
6.05	1.22	0.58	0.50	0.63	1.01	1.57	2.36
6.10	1.61	0.83	0.60	0.55	0.73	1.09	1.67
6.15	2.11	1.19	0.81	0.59	0.59	0.76	1.14
6.20	2.73	1.67	1.16	0.77	0.60	0.58	0.79
6.25		2.27	1.62	1.07	0.74	0.56	0.59
6.30		2.97	2.19	1.49	1.00	0.66	0.53
6.35			2.85	2.01	1.38	0.88	0.60
6.40				2.63	1.84	1.20	0.78
6.45					2.39	1.61	1.04
6.50					2.99	2.08	1.38
6.55						2.58	1.75
6.60							2.15
6.65							2.56
6.70							2.99

*The processes included are collisional ionization, radiative recombination and dielectronic recombination.

TABLE 6 Continued

IRON RELATIVE ION POPULATIONS*

Stage of Ionization (m+1)

log T	XIV	XV	XVI	XVII	XVIII	XIX
6.10	2.60					
6.15	1.85	2.91				
6.20	1.28	2.11				
6.25	0.88	1.50	2.26			
6.30	0.63	1.06	1.61	2.35		
6.35	0.52	0.76	1.12	1.79		
6.40	0.54	0.60	0.78	1.37		
6.45	0.64	0.55	0.55	1.07	2.93	
6.50	0.83	0.57	0.41	0.86	2.49	
6.55	1.06	0.66	0.33	0.71	2.13	
6.60	1.32	0.78	0.30	0.59	1.82	
6.65	1.61	0.92	0.29	0.50	1.55	2.74
6.70	1.90	1.08	0.32	0.44	1.31	2.32
6.75	2.21	1.26	0.36	0.39	1.10	1.94
6.80	2.54	1.46	0.42	0.36	0.91	1.59
6.85	2.88	1.68	0.52	0.36	0.76	1.29
6.90		1.94	0.64	0.39	0.64	1.02
6.95		2.23	0.81	0.46	0.57	0.81
7.00		2.56	1.02	0.58	0.56	0.66
7.05		2.95	1.29	0.74	0.59	0.56
7.10			1.61	0.96	0.68	0.52
7.15			1.96	1.21	0.81	0.52
7.20			2.34	1.50	0.97	0.56
7.25			2.74	1.80	1.15	0.62
7.30				2.10	1.35	0.70
7.35				2.42	1.55	0.78
7.40				2.74	1.75	0.87
7.45					1.96	0.97
7.50					2.17	1.07
7.55					2.38	1.17
7.60					2.59	1.27
7.65					2.80	1.37
7.70						1.47
7.75						1.57
7.80						1.68
7.85						1.78
7.90						1.88
7.95						1.98
8.00						2.08

*See footnote on preceding page.

TABLE 7

IRON RELATIVE ION POPULATIONS*: $-\log N(Fe^{+m})/N_{tot}$

Stage of Ionization (m+1)

log T	VII	VIII	IX	X	XI	XII	XIII
5.00	2.83						
5.05	2.32						
5.10	1.88						
5.15	1.52						
5.20	1.22						
5.25	0.96						
5.30	0.75	2.69					
5.35	0.58	2.22					
5.40	0.45	1.82					
5.45	0.35	1.47					
5.50	0.28	1.17	2.54				
5.55	0.25	0.92	2.07				
5.60	0.24	0.72	1.66				
5.65	0.27	0.57	1.32				
5.70	0.34	0.46	1.03	2.81			
5.75	0.43	0.39	0.80	2.29			
5.80	0.56	0.36	0.61	1.84			
5.85	0.72	0.37	0.48	1.45	2.75		
5.90	0.91	0.42	0.39	1.13	2.17		
5.95	1.13	0.51	0.34	0.87	1.67	2.68	
6.00	1.39	0.64	0.35	0.67	1.25	2.02	
6.05	1.71	0.83	0.41	0.54	0.92	1.48	2.27
6.10	2.10	1.10	0.56	0.51	0.69	1.04	1.62
6.15	2.58	1.46	0.80	0.57	0.58	0.74	1.13
6.20		1.93	1.15	0.76	0.59	0.58	0.78
6.25		2.51	1.62	1.07	0.74	0.56	0.59
6.30			2.20	1.50	1.01	0.67	0.54
6.35			2.88	2.04	1.40	0.91	0.63
6.40				2.70	1.91	1.27	0.85
6.45					2.52	1.74	1.18
6.50						2.27	1.57
6.55						2.83	2.00
6.60							2.45
6.65							2.90

*The processes included are collisional ionization, collisional excitation of autoionizing levels, radiative recombination and dielectronic recombination.

TABLE 7 Continued

IRON RELATIVE ION POPULATIONS*

Stage of Ionization (m+1)

log T	XIV	XV	XVI	XVII	XVIII	XIX
6.10	2.56					
6.15	1.83	2.89				
6.20	1.27	2.11				
6.25	0.88	1.50	2.16	2.62		
6.30	0.64	1.07	1.50	1.85		
6.35	0.55	0.79	1.02	1.28		
6.40	0.60	0.67	0.71	0.88	2.96	
6.45	0.78	0.68	0.53	0.62	2.46	
6.50	1.02	0.77	0.45	0.47	2.07	
6.55	1.31	0.91	0.43	0.37	1.77	
6.60	1.62	1.07	0.44	0.30	1.51	2.89
6.65	1.94	1.25	0.48	0.26	1.29	2.48
6.70	2.26	1.44	0.53	0.24	1.09	2.10
6.75	2.60	1.64	0.60	0.23	0.92	1.76
6.80	2.94	1.86	0.69	0.24	0.78	1.46
6.85		2.09	0.80	0.27	0.66	1.18
6.90		2.35	0.93	0.33	0.58	0.95
6.95		2.64	1.10	0.43	0.53	0.76
7.00		2.97	1.32	0.56	0.53	0.63
7.05			1.58	0.74	0.58	0.55
7.10			1.89	0.96	0.68	0.51
7.15			2.23	1.22	0.81	0.52
7.20			2.60	1.50	0.97	0.56
7.25			2.99	1.80	1.15	0.62
7.30				2.11	1.35	0.70
7.35				2.42	1.55	0.78
7.40				2.74	1.75	0.87
7.45					1.96	0.97
7.50					2.17	1.07
7.55					2.38	1.17
7.60					2.59	1.27
7.65					2.80	1.37
7.70						1.47
7.75						1.57
7.80						1.68
7.85						1.78
7.90						1.88
7.95						1.98
8.00						2.08

*See footnote on preceding page.

TABLE 8

EFFECTS OF DIELECTRONIC RECOMBINATION ON THE IONIZATION EQUILIBRIUM

	RADIATIVE RECOMBINATION ONLY				WITH DIELECTRONIC RECOMBINATION			
Ion	log T_{max}	-log N_{max}	log T_1	log T_2	log T_{max}	-log N_{max}	log T_1	log T_2
OXYGEN								
II	4.40	0.001	4.10	4.66	4.42	0.002	4.10	4.82
III	4.76	0.038	4.60	4.93	4.94	0.084	4.70	5.21
IV	5.00	0.083	4.85	5.16	5.24	0.184	5.03	5.45
V	5.21	0.116	5.06	5.37	5.42	0.302	5.26	5.55
VI	5.39	0.186	5.25	5.57	5.51	0.623	5.39	5.67
VII	5.94	0.004	5.44	6.31	5.94	0.005	5.50	6.38
VIII	6.35	0.236	6.18	6.58	6.38	0.346	6.18	6.61
NEON								
II	4.51	0.006	4.30	4.71	4.51	0.006	4.30	4.77
III	4.81	0.040	4.66	4.98	4.91	0.056	4.68	5.18
IV	5.06	0.065	4.90	5.22	5.25	0.13	5.03	5.49
V	5.26	0.14	5.13	5.40	5.50	0.23	5.30	5.71
VI	5.43	0.17	5.29	5.57	5.69	0.27	5.50	5.84
VII	5.58	0.23	5.45	5.73	5.79	0.52	5.65	5.92
VIII	5.73	0.25	5.59	5.92	5.86	0.68	5.74	6.04
IX	6.23	0.010	5.76	6.60	6.24	0.012	5.84	6.67
X	6.64	0.27	6.45	6.89	6.67	0.38	6.45	6.93

TABLE 8 Continued

Ion	RADIATIVE RECOMBINATION ONLY				WITH DIELECTRONIC RECOMBINATION			
	log T_{max}	-log N_{max}	log T_1	log T_2	log T_{max}	-log N_{max}	log T_1	log T_2
SILICON								
II	4.12	0.004	<4.00	4.35	4.15	0.008	<4.00	4.61
III	4.50	0.016	4.29	4.71	4.75	0.080	4.44	4.93
IV	4.77	0.092	4.63	4.94	4.90	0.643	4.78	5.03
V	5.20	0.006	4.85	5.47	5.23	0.006	4.90	5.64
VI	5.50	0.204	5.37	5.62	5.68	0.213	5.47	5.89
VII	5.62	0.241	5.51	5.75	5.85	0.398	5.68	6.03
VIII	5.75	0.249	5.63	5.88	5.97	0.404	5.81	6.16
IX	5.86	0.293	5.74	5.99	6.09	0.376	5.92	6.27
X	5.97	0.309	5.85	6.11	6.21	0.426	6.05	6.35
XI	6.09	0.313	5.95	6.25	6.28	0.577	6.14	6.44
XII	6.22	0.308	6.07	6.46	6.36	0.684	6.22	6.63
XIII	6.68	0.026	6.24	7.06	6.70	0.034	6.33	7.12
XIV	7.08	0.313	6.86	7.40	7.12	0.403	6.87	7.44

TABLE 8 Continued

IRON

Ion	RADIATIVE RECOMBINATION ONLY				WITH DIELECTRONIC RECOMBINATION			
	log T_{max}	-log N_{max}	log T_1	log T_2	log T_{max}	-log N_{max}	log T_1	log T_2
VII	5.34	0.19	5.20	5.49	5.68	0.23	5.38	5.95
VIII	5.49	0.24	5.35	5.62	5.91	0.33	5.68	6.10
IX	5.61	0.26	5.49	5.73	6.03	0.49	5.85	6.17
X	5.71	0.35	5.60	5.82	6.11	0.55	5.97	6.24
XI	5.79	0.37	5.69	5.91	6.17	0.58	6.04	6.31
XII	5.87	0.36	5.77	5.99	6.24	0.55	6.11	6.37
XIII	5.96	0.39	5.85	6.08	6.30	0.53	6.17	6.44
XIV	6.05	0.36	5.93	6.18	6.37	0.51	6.24	6.53
XV	6.14	0.37	6.01	6.31	6.46	0.55	6.31	6.68
XVI	6.27	0.34	6.11	6.49	6.63	0.29	6.40	6.94
XVII	6.47	0.16	6.25	6.66	6.83	0.36	6.51	7.07
XVIII	6.63	0.44	6.48	6.78	6.99	0.56	6.77	7.22
XIX	6.74	0.43	6.59	6.97	7.12	0.52	6.91	7.46

TABLE 9

APPLICABILITY OF PRESENT DENSITY INDEPENDENT CALCULATIONS

ION	N_e (cm^{-3})			
	10^7	10^8	10^9	10^{10}
O	V-IX	VII-IX	VIII-IX	IX
Ne	V-XI	VII-XI	IX-XI	XI
Si	V-XV	VII-XV	IX-XV	XIII-XV
Fe	VII-XIX	VII-XIX	IX-XIX	XIII-XIX

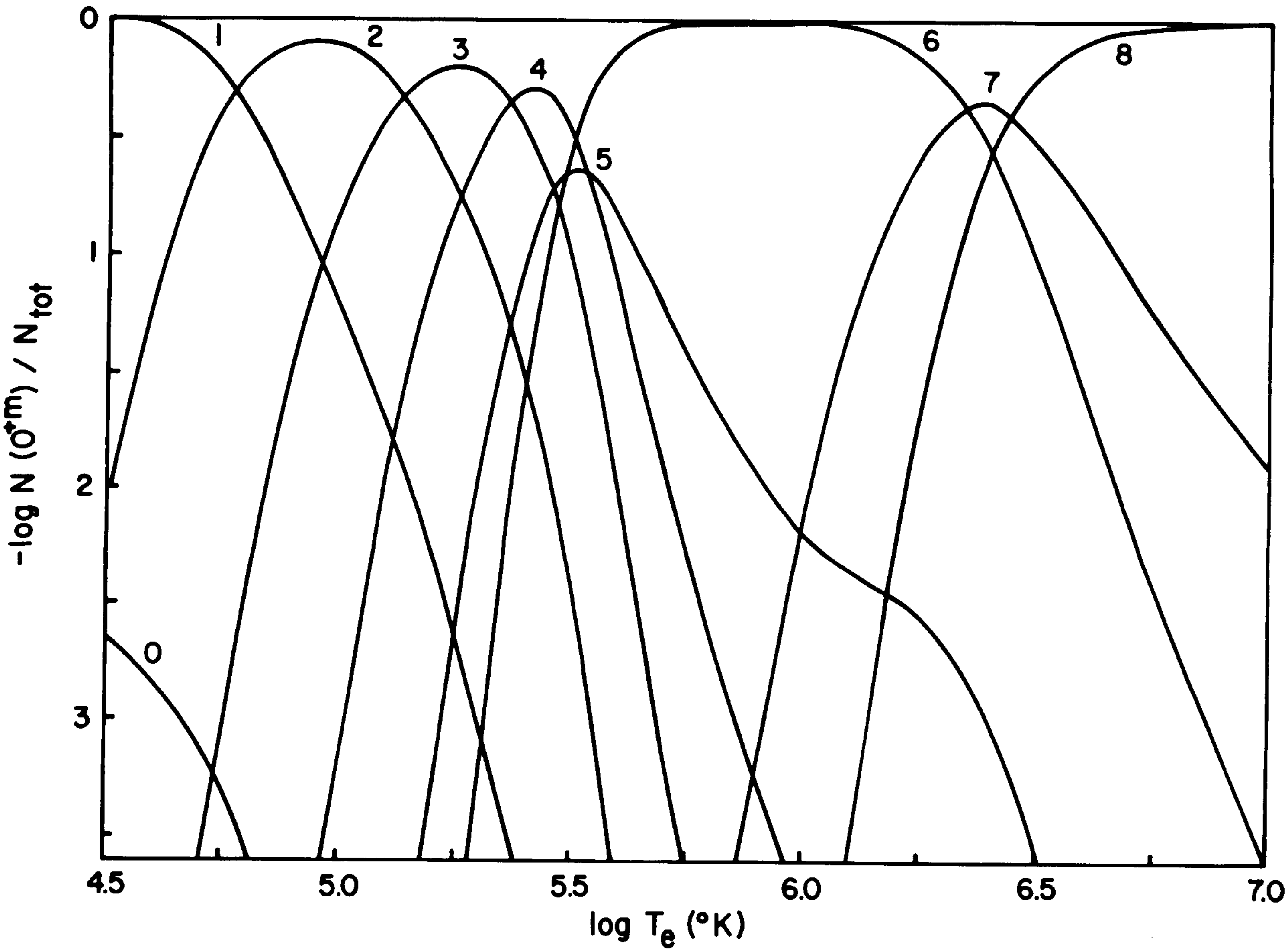

Figure 1: Relative Ion Populations for Oxygen. The processes of collisional ionization, collisional excitation to autoionizing levels, radiative recombination, and dielectronic recombination are included. Each curve is labeled with the value of m; note O^{+2} is equivalent to O III.

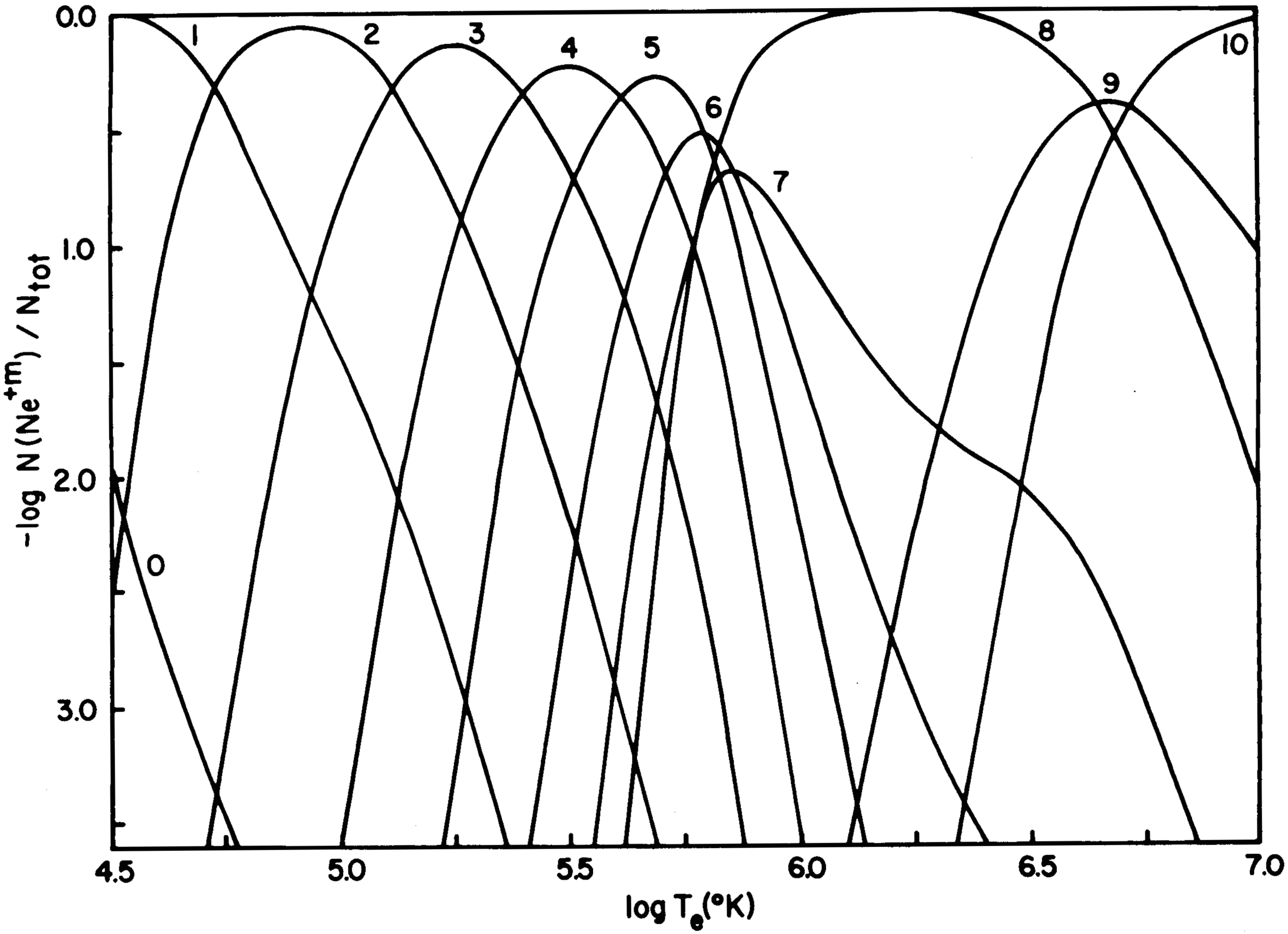

Figure 2: Relative Ion Populations for Neon. The processes of collisional ionization, radiative recombination, and dielectronic recombination are included. Collisional excitation to autoionizing levels is not important and has not been included. Each curve is labeled with the value of m; note Ne^{+2} is equivalent to Ne III.

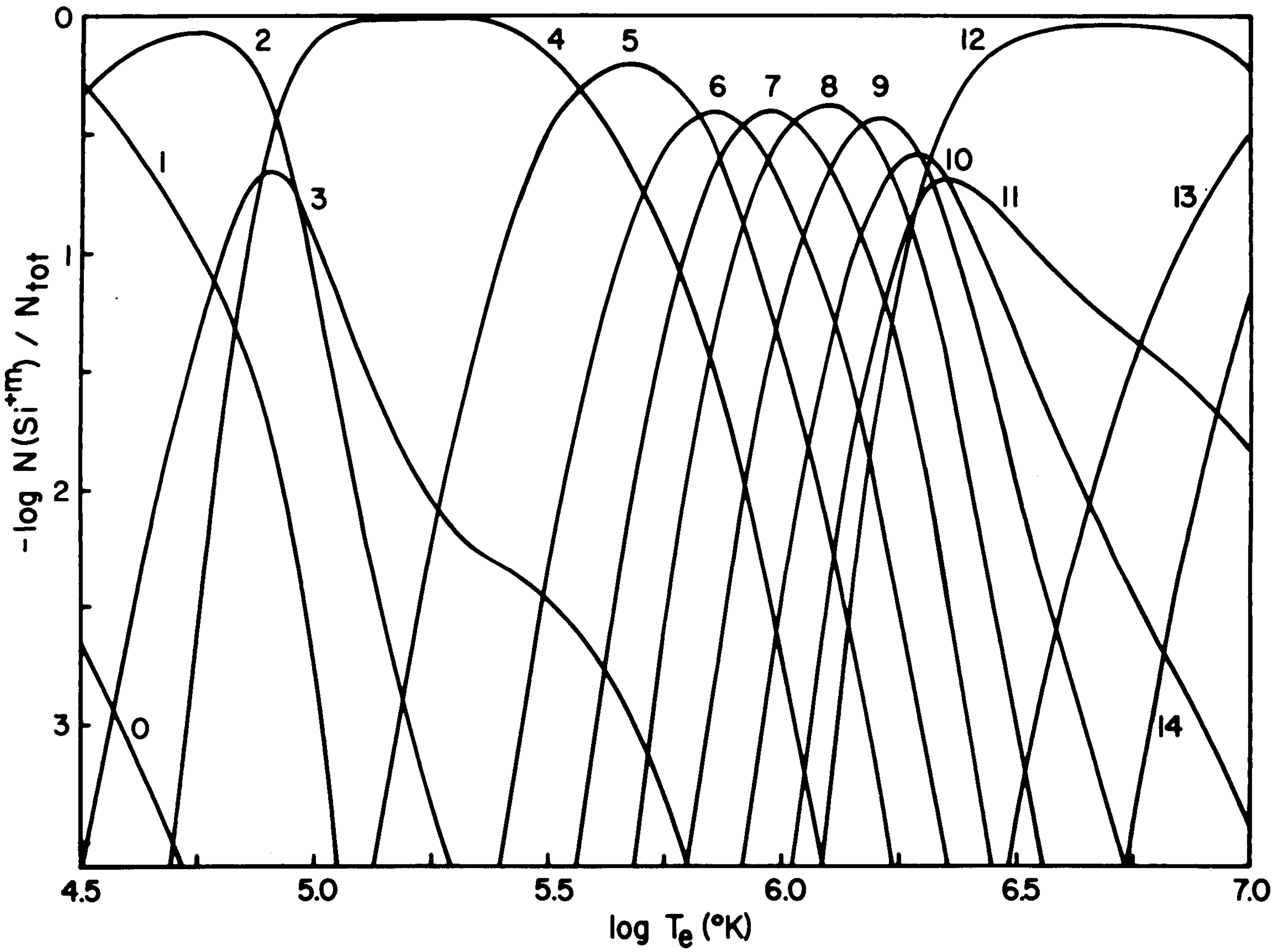

Figure 3: Relative Ion Populations for Silicon. The processes of collisional ionization, collisional excitation to autoionizing levels, radiative recombination, and dielectronic recombination are included. Each curve is labeled with the value of m; note Si^{+2} is equivalent to Si III.

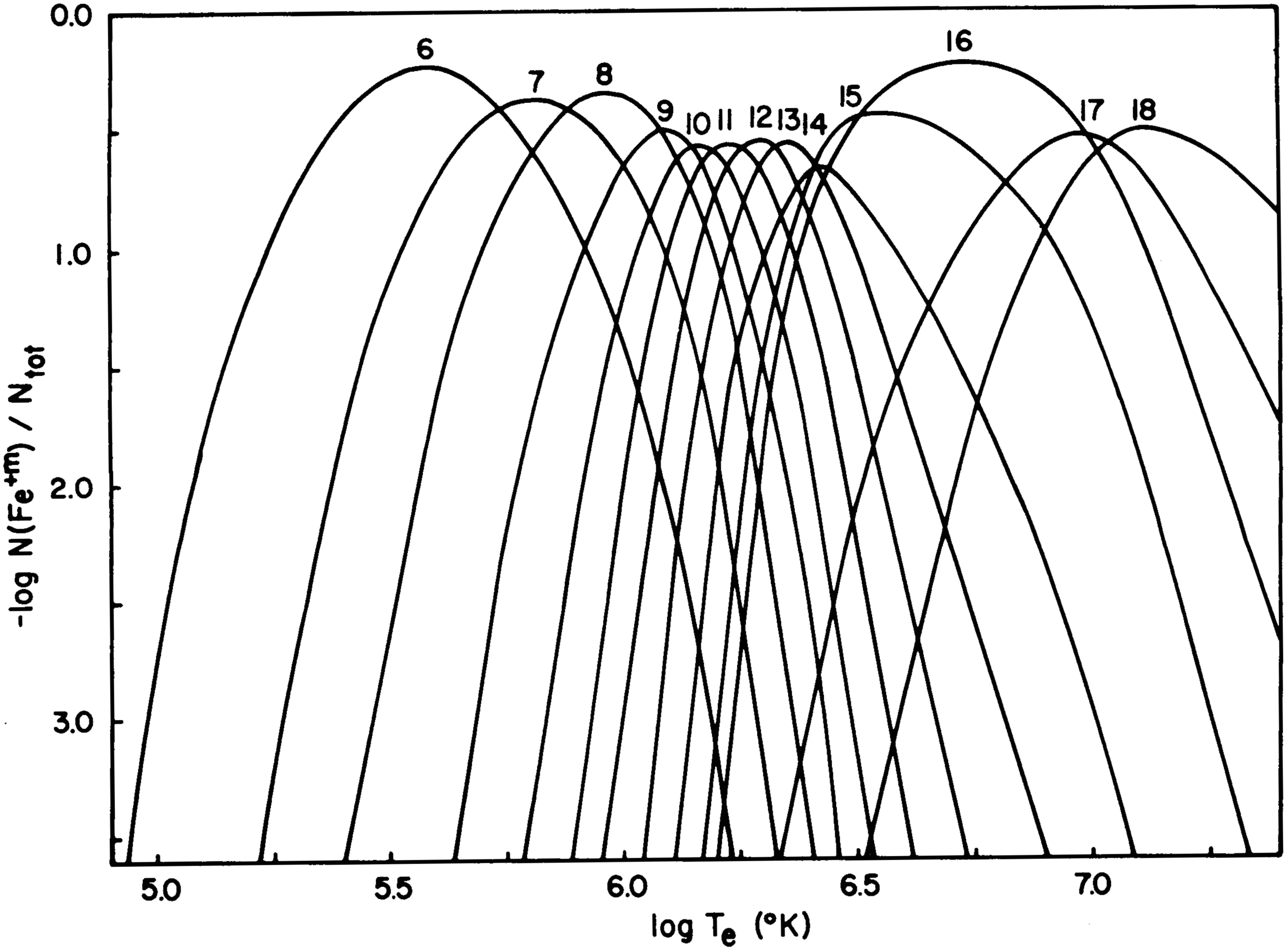

Figure 4: Relative Ion Populations for Iron. The processes of collisional ionization, collisional excitation to autoionizing levels, radiative recombination, and dielectronic recombination are included. Each curve is labeled with the value of m; note Fe^{+9} is equivalent to Fe X.