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Menas Kafatos
Chapman University, kafatos@chapman.edu

J. P. Lynch
Agr & Agri Food Canada

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FORBIDDEN LINES OF np^q IONS. I. DETAILED BALANCE AND LINE INTENSITY RATIOS

MINAS KAFATOS[1]
Department of Physics, George Mason University;
and Laboratory for Astronomy and Solar Physics, NASA Goddard Space Flight Center

AND

JOHN P. LYNCH[2]
Department of Physics, George Mason University

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ABSTRACT

Forbidden transitions in the ground state levels of np^q ions can provide important information on the state of hot gases. In particular, transitions in $q=2,4$ ions (e.g., O I, O III, Ne III, Ne V, etc.) can give information on the temperature of the gas, whereas transitions in $q=3$ ions (e.g., O II, Ne IV, Fe XII, etc.) can give information on the density of the gas. We have solved the detailed balance equations in the ground state terms of 37 ions of C, N, O, Ne, Mg, Si, S, and Fe. The ions examined are abundant for temperatures in the approximate range 5×10^3–2×10^6 K and could provide important information on the hot ($10^4 \lesssim T \lesssim 10^6$ K) component of the interstellar medium. We have tabulated the atomic data for 235 transitions of these ions and graphed 14 line ratios of $q=2,4$ ions and eight line ratios of $q=3$ ions. The relative populations of the various levels are given in tabular form and can be used for the calculations of the absolute line intensities if the ionic abundances are known. Forbidden emission lines of these ions are in the far and near UV, visible, and near and far IR regions of the spectrum. These calculations are important for studies of the solar transition region, H II regions and planetary nebulae, supernova remnants, and interstellar bubbles produced by stellar winds.

Subject headings: atomic processes — transition probabilities

I. INTRODUCTION

Forbidden transitions in the ground state of np^q ions are electric quadrupole and magnetic dipole transitions which are from collisional excitations by thermal electrons. These ions make a significant contribution to the cooling of the hot plasma, and their forbidden lines have been computed theoretically and applied to observations of many H II regions and planetary nebulae (see, e.g., Shortley and Menzel 1940; Hebb and Menzel 1940; Menzel and Aller 1941; Menzel, Aller, and Hebb 1941; Aller 1954, 1957; Seaton 1954, 1960; Osterbrock 1960, 1974; O'Dell 1963; Peimbert and Torres-Peimbert 1971; etc.). Ratios of forbidden lines for particular transitions of an ion can provide a means of determining the electron density (Seaton 1954) or temperature (Menzel, Aller, and Hebb 1941) of the ionized plasma.

The vast majority of the lines examined in the literature are in the visible or near ultraviolet (UV) region of the spectrum. Recently, as a result of new advances in astronomy, forbidden lines in the far UV, as well as near and far infrared (IR) regions of the spectrum have been studied (e.g., Flower and Nussbaumer 1975; Delmer, Gould, and Ramsay 1967). These advances are not limited to interstellar gas regions, but include important observations of the *EUV* solar spectrum (e.g., Jordan 1971).

It would seem particularly desirable for workers in the field to refer to a complete set of calculations for these forbidden lines. For this purpose, we present detailed calculations of the relative populations of the levels of the ground state as a function of temperature and density. We also present calculations of the ratios for lines of the same ion. In this work, the ions of C, N, O, Ne, Mg, Si, S, and Fe with electron configurations np^q, where $n=2,3$ and $q=1,2,3,4,5$ are treated.

In a future paper we will treat ions of other elements—such as Cl, Ar, and Ni—which are also of astrophysical significance. Their inclusion in the present work would have made it prohibitively long. Moreover these ions have not been treated by either Kafatos (1973) or Shapiro and Moore (1976), and therefore their relative ionic abundances can only be treated in the case when recombinations balance collisional ionizations. In this respect, we distinguish them

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[1] Work supported by NASA grant NSG 5305.
[2] Now at Systems Sciences Division, Computer Sciences Corporation.

from the ions treated in this work. In order to carry out the calculations, we have tried to use the most recent calculations of the atomic data needed; when they were not available, we made interpolations along isoelectronic sequences. Although these are not, of course, the only elements with np^q ions, they are the most abundant heavy elements, and their lines are expected, in general, to be stronger than those of less abundant elements such as Ar, Ca, Ni, etc. Moreover, we have limited ourselves to ions which are expected to be abundant for temperatures in the approximate range 5×10^3–2×10^6 K. Radiative cooling of the hot plasma is high in this range, and it achieves its maximum value at $T\approx10^5$ K (Cox and Tucker 1969; Kafatos 1973). The solar transition region and the interstellar gas under widely different conditions lie in this range: H II regions and planetaries at the low end of the temperature range; cooling supernova shocks in the isothermal phase (Spitzer 1978); and interstellar bubbles at the high end of the temperature range (Castor, McCray, and Weaver 1975). Hot interstellar plasmas above 10^5 K have been observed very little with the exception of the *Copernicus* observations (Jenkins and Meloy 1974; York 1974, 1977).

We limit ourselves to calculations of the relative populations of the levels and line intensity ratios. In a future work, the actual line intensities will be presented in a number of interesting cases. The present results can, however, be used for line intensity calculations if one knows the relevant ionic abundances.

II. DATA AND EQUATIONS

The line intensity can be found from the equation

$$I_{ji}=A_{ji}N_jN_{A,Z}N_Ah\nu_{ji}\frac{n}{1+N_{\mathrm{He}}}L/4\pi \text{ ergs cm}^{-2}\text{s}^{-1}\text{sr}^{-1}, \tag{1}$$

where A_{ji} is the radiative transition probability from upper level j to lower level i, N_j is the relative population of level j, $N_{A,Z}$ is the relative ionic abundance of ion with charge Z of element with atomic number A, N_A is the relative (with respect to hydrogen) chemical abundance, ν_{ji} is the frequency of transition, N_{He} the relative chemical abundance of helium, n is the total number density of hydrogen and helium nuclei (in cm^{-3}), and L is the path length through the line emitting region. From this point on we will use the following convention: capital letters N refer to relative abundances while lower case letters n refer to number densities.

It is obvious from equation (1) that the line intensity can be determined once the relative populations of the levels have been computed and if we know the ionic abundance. The latter depends on the specific region under consideration (for example, purely collisional ionization would produce a different abundance from radiative ionization, etc.).

The relative population of the level N_j is a function of temperature and density only. On the other hand, by taking ratios of lines of the same ion one obtains a relation which is a function of the atomic parameters, the temperature, and the density, and does not depend on the specific conditions of ionization and recombination. The ratio of two lines of the same ion is

$$\frac{I_{ji}}{I_{lk}}=\frac{A_{ji}\nu_{ji}N_j}{A_{lk}\nu_{lk}N_l}, \tag{2}$$

where j and l are the upper levels while i and k are the lower levels.

It is evident from equations (1) and (2) that whether absolute intensities or relative line intensities are needed, the relative populations N_j are needed.

We have computed the relative populations N_j, $j=1,2,3,4,5$ for the $n=2,3$ and $q=2,3,4$ np^q ions, and the populations N_j, $j=1,2$ for the $n=2,3$ and $q=1,5$ np^q ions.

Ions with $q=3$ have the single level ^4S as the lowest energy level of the ground state term, with the doublet ^2D above it and the doublet ^2P above ^2D. Ions with $q=2,4$ have the triplet ^3P as the lowest energy levels, with the singlet ^1D above them and the singlet ^1S above ^1D. Ions with $q=1,5$ have a doublet ^2P in their ground state term.

The necessary algebraic equations for the computation of the N_j's are given in Appendix A for the five level ions. The equations for the two level ($q=1,5$) ions are not given, since they are trivial. These equations can be used in any five level ion and, therefore, apply beyond the specific ions examined in the present paper. They are, of course, the balance equations which express the relative number of ions in each level j determined by balancing collisional excitation from lower levels to j and from j to higher levels, collisional de-excitation from higher levels to j and from j to lower levels, and, finally, radiative transitions from higher levels to j and from j to lower levels. This system of equations is given in the Appendix in equations (A1) and (A3).

The atomic data needed in order to compute the N_j are the following: (a) the wavelengths (or energy differences) for the transitions, (b) the radiative transition probabilities, and (c) the collision strengths.

There are numerous papers on these atomic data and, of course, quite often duplication. In choosing the appropriate data we tried to use the most recent work and, where more than one paper existed, the papers which had more extensive computations. Useful references were provided to us by R. Garstang. We checked for discrepancies in the published data between different sources and found that generally there were no serious discrepancies (they were not more than, say, 10%). Quite often we left out the original articles and used convenient references (e.g., Osterbrock 1974) where the atomic data are reviewed. Including all original references would make the manuscript very long. Moreover, it is not our purpose to review the literature, but only to provide the most up-to-date calculations which can be used by the workers in the field.

In the few cases where no work existed on the required collision strengths we interpolated along the isoelectronic sequences. Even though it is not the purpose of this paper to review the literature, we are confident that the data used provide a reasonable sample for our computations.

The data used in the present paper are compiled in Tables 1A–1V and Table 2. The corresponding ions for Tables 1A–1V (with $q=2,3,4$) are the following: N I, Table 1A; N II, 1B; O I, 1C; O II, 1D; O III, 1E; Ne III, 1F; Ne IV, 1G; Ne V, 1H; Mg V, 1I; Mg VI, 1J; Mg VII, 1K; Si VII, 1L; Si VIII, 1M; Si IX, 1N; S II, 1O; S III, 1P; S IX, 1Q; S X, 1R; S XI, 1S; Fe XI, 1T; Fe XII, 1U; Fe XIII, 1V. In Table 2, the data for $q=1,5$ ions are given. In each of the Tables 1A–1V we have included: column (1), the relevant transition (upper to lower level); column (2), the wavelength in A; column (3), the source in the literature for the wavelength; column (4), the transition probability in s^{-1}; column (5), the literature source for the transition probability; column (6), the collision strength; and column (7), the literature source for the collision strength. Similar information is given in Table 2. Whenever the collision strength values were obtained by interpolation, this was indicated by the letter I; the procedure used was given in a note to the particular table.

The transition probabilities listed in the tables are the sum of the electric quadrupole and the magnetic dipole transition probabilities.

The collision strengths for the multiplet are often given in the literature. Sum rules are, therefore, needed to find the collision strengths between individual levels of the multiplet. The following sum rules were used (see also Saraph, Seaton, and Shemming 1968; Osterbrock 1974):

i) $q=3$: $\Omega(^4S,{}^2D_J)=\frac{1}{10}(2J+1)\Omega(^4S,{}^2D)$,
$\Omega(^4S,{}^2P_J)=\frac{1}{6}(2J+1)\Omega(^4S,{}^2P)$;

ii) $q=2,4$: $\Omega(^1S,{}^3P_J)=\frac{1}{9}(2J+1)\Omega(^1S,{}^3P)$,
$\Omega(^1D,{}^3P_J)=\frac{1}{9}(2J+1)\Omega(^1D,{}^3P)$,

where the collision strengths in the right hand side of the above relations are given in the literature. These sum rules pertain from one to many levels or from many levels to one (the collision strength between two levels is symmetrical, i.e., $\Omega_{ij}=\Omega_{ji}$). For transitions between many levels, e.g., the ^2P to ^2D transitions in $q=3$ ions, the collision strengths must be interpolated independently.

TABLE 1A

ION N I; CONFIGURATION $2p^3$

Transition	Wavelength λ(Å)	Wavelength Data Source	Transition Probability $A(s^{-1})$	Transition Probability Data Source	Collision Strength Ω	Collision Strength Data Source
$^2D_{5/2}-{}^4S_{3/2}$..........	5201.7	E	6.9×10^{-6}	G1	[a]	O
$^2D_{3/2}-{}^4S_{3/2}$..........	5199.3	E	1.6×10^{-5}	G1	[a]	O
$^2P_{1/2}-{}^4S_{3/2}$..........	3467.5	E	2.5×10^{-3}	G1	[a]	KP
$^2P_{3/2}-{}^4S_{3/2}$..........	3467.5	E	6.2×10^{-3}	G1	[a]	KP
$^2D_{3/2}-{}^2D_{5/2}$..........	1.149×10^7	E	1.3×10^{-8}	G1	[a]	O
$^2P_{1/2}-{}^2D_{5/2}$..........	10401.1	E	0.031	G1	[a]	KP[b]
$^2P_{3/2}-{}^2D_{5/2}$..........	10400.6	E	0.054	G1	[a]	KP[b]
$^2P_{1/2}-{}^2D_{3/2}$..........	10410.5	E	0.047	G1	[a]	KP[b]
$^2P_{3/2}-{}^2D_{3/2}$..........	10410.1	E	0.025	G1	[a]	KP[b]
$^2P_{3/2}-{}^2P_{1/2}$..........	2.5×10^8	E	very small	G1	[a]	[c]

[a] Function of temperature.

[b] KP: Assumed $\frac{1}{4}$ of total $^2P-{}^2D$ collision strength.

[c] Not given, so assumed to be the same as for $^2D_{3/2}-{}^2D_{5/2}$.

TABLE 1B

ION N II; CONFIGURATION $2p^3$

Transition	Wavelength λ(Å)	Wavelength Data Source	Transition Probability $A(s^{-1})$	Transition Probability Data Source	Collision Strength Ω	Collision Strength Data Source
$^3P_1-^3P_0$	2.053×10^6	E	2.1×10^{-6}	G1	0.401	SSS
$^3P_2-^3P_0$	7.645×10^5	E	1.3×10^{-12}	G1	0.279	SSS
$^1D_2-^3P_0$	6529.0	E	4.2×10^{-7}	G1	0.349	CKMSS
$^1S_0-^3P_0$	3059.2	E	0.0	...	0.038	SSS
$^3P_2-^3P_1$	1.218×10^6	E	7.5×10^{-6}	G1	1.128	SSS
$^1D_2-^3P_1$	6549.8	E	1.03×10^{-3}	G1	1.047	CKMSS
$^1S_0-^3P_1$	3063.7	E	0.034	G1	0.114	SSS
$^1D_2-^3P_2$	6585.2	E	3.0×10^{-3}	G1	1.744	CKMSS
$^1S_0-^3P_2$	3071.4	E	1.6×10^{-4}	G1	0.190	SSS
$^1S_0-^1D_2$	5756.2	E	1.08	G1	0.376	SSS

SSS and CKMSS are in agreement whenever common collision strength values were computed.

TABLE 1C

ION O I; CONFIGURATION $2p^4$

Transition	Wavelength λ(Å)	Wavelength Data Source	Transition Probability $A(s^{-1})$	Transition Probability Data Source	Collision Strength Ω	Collision Strength Data Source
$^3P_1-^3P_2$	6.317×10^5	E	9.0×10^{-5}	G1	[a]	O
$^3P_0-^3P_2$	4.405×10^5	E	1.0×10^{-10}	G1	[a]	O
$^1D_2-^3P_2$	6302.0	E	5.1×10^{-3}	G1	[a]	O
$^1S_0-^3P_2$	2959.2	E	3.7×10^{-4}	G1	[a]	O
$^3P_0-^3P_1$	1.456×10^6	E	1.7×10^{-5}	G1	[a]	O
$^1D_2-^3P_1$	6365.5	E	1.64×10^{-3}	G1	[a]	O
$^1S_0-^3P_1$	2973.2	E	0.067	G1	[a]	O
$^1D_2-^3P_0$	6393.5	E	1.1×10^{-6}	G1	[a]	O
$^1S_0-^3P_0$	2979.2	E	0.0	...	[a]	O
$^1S_0-^1D_2$	5578.9	E	1.34	G1	[a]	KP

[a] Function of temperature.

TABLE 1D

ION O II; CONFIGURATION $2p^3$

Transition	Wavelength λ(Å)	Wavelength Data Source	Transition Probability $A(s^{-1})$	Transition Probability Data Source	Collision Strength Ω	Collision Strength Data Source
$^2D_{5/2}-^4S_{3/2}$	3729.9	E	4.8×10^{-5}	G1	0.858	SSS
$^2D_{3/2}-^4S_{3/2}$	3727.1	E	1.70×10^{-4}	G1	0.572	SSS
$^2P_{3/2}-^4S_{3/2}$	2471.1	E	0.060	G1	0.285	SSS
$^2P_{1/2}-^4S_{3/2}$	2471.1	E	0.0238	G1	0.143	SSS
$^2D_{3/2}-^2D_{5/2}$	5.128×10^6	E	1.3×10^{-7}	G1	0.894	SSS
$^2P_{3/2}-^2D_{5/2}$	7322.4	E	0.115	G1	0.743	SSS
$^2P_{1/2}-^2D_{5/2}$	7321.8	E	0.061	G1	0.302	SSS
$^2P_{3/2}-^2D_{3/2}$	7332.8	E	0.061	G1	0.418	SSS
$^2P_{1/2}-^2D_{3/2}$	7332.2	E	0.100	G1	0.279	SSS
$^2P_{1/2}-^2P_{3/2}$	9.091×10^7	E	6.0×10^{-11}	G1	0.263	SSS

TABLE 1E

ION O III; CONFIGURATION $2p^2$

Transition	Wavelength λ(Å)	Wavelength Data Source	Transition Probability A(s^{-1})	Transition Probability Data Source	Collision Strength Ω	Collision Strength Data Source
${}^3P_1-{}^3P_0$	8.834×10^5	E	2.6×10^{-5}	G1	0.376	SSS
${}^3P_2-{}^3P_0$	3.266×10^5	E	3.5×10^{-11}	G1	0.213	SSS
${}^1D_2-{}^3P_0$	4932.6	E	1.9×10^{-6}	G1	0.266	SSS
${}^1S_0-{}^3P_0$	2315.6	E	0.0	...	0.037	SSS
${}^3P_2-{}^3P_1$	5.181×10^5	E	9.8×10^{-5}	G1	0.948	SSS
${}^1D_2-{}^3P_1$	4960.3	E	0.0071	G1	0.797	SSS
${}^1S_0-{}^3P_1$	2321.7	E	0.23	G1	0.112	SSS
${}^1D_2-{}^3P_2$	5008.2	E	0.021	G1	1.33	SSS
${}^1S_0-{}^3P_2$	2332.1	E	7.1×10^{-4}	G1	0.186	SSS
${}^1S_0-{}^1D_2$	4364.4	E	1.60	G1	0.310	SSS

TABLE 1F

ION Ne III; CONFIGURATION $2p^4$

Transition	Wavelength λ(Å)	Wavelength Data Source	Transition Probability A(s^{-1})	Transition Probability Data Source	Collision Strength Ω	Collision Strength Data Source
${}^3P_1-{}^3P_2$	1.556×10^5	E	6.0×10^{-3}	G1	0.527	SSS
${}^3P_3-{}^3P_2$	1.086×10^5	E	2.0×10^{-8}	G1	0.1314	SSS
${}^1D_2-{}^3P_2$	3869.8	E	0.17	G1	0.706	SSS
${}^1S_0-{}^3P_2$	1793.8	E	5.1×10^{-3}	G1	0.091	SSS
${}^3P_0-{}^3P_1$	3.597×10^5	E	1.2×10^{-3}	G1	0.1845	SSS
${}^1D_2-{}^3P_1$	3968.5	E	0.052	G1	0.423	SSS
${}^1S_0-{}^3P_1$	1814.7	E	2.2	G1	0.055	SSS
${}^1D_2-{}^3P_0$	4012.8	E	1.2×10^{-5}	G1	0.141	SSS
${}^1S_0-{}^3P_0$	1823.9	E	0.0	...	0.018	SSS
${}^1S_0-{}^1D_2$	3343.6	E	2.8	G1	0.188	SSS

TABLE 1G

ION Ne IV; CONFIGURATION $2p^3$

Transition	Wavelength λ(Å)	Wavelength Data Source	Transition Probability A(s^{-1})	Transition Probability Data Source	Collision Strength Ω	Collision Strength Data Source
${}^2D_{5/2}-{}^4S_{3/2}$	2425.1	E	5.9×10^{-4}	G1	0.624	SSS
${}^2D_{3/2}-{}^4S_{3/2}$	2422.5	E	5.6×10^{-3}	G1	0.416	SSS
${}^2P_{1/2}-{}^4S_{3/2}$	1601.7	E	0.53	G1	0.142	SSS
${}^2P_{3/2}-{}^4S_{3/2}$	1601.5	E	1.33	G1	0.285	SSS
${}^2D_{3/2}-{}^2D_{5/2}$	2.227×10^6	E	1.4×10^{-6}	G1	0.817	SSS
${}^2P_{1/2}-{}^2D_{5/2}$	4717.0	E	0.11	G1	0.246	SSS
${}^2P_{3/2}-{}^2D_{5/2}$	4715.5	E	0.40	G1	0.619	SSS
${}^2P_{1/2}-{}^2D_{3/2}$	4727.0	E	0.39	G1	0.234	SSS
${}^2P_{3/2}-{}^2D_{3/2}$	4725.5	E	0.44	G1	0.342	SSS
${}^2P_{3/2}-{}^2P_{1/2}$	1.493×10^7	E	2.3×10^{-9}	G1	0.446	SSS

TABLE 1H

ION Ne V; CONFIGURATION $2p^2$

Transition	Wavelength λ(Å)	Wavelength Data Source	Transition Probability $A(s^{-1})$	Transition Probability Data Source	Collision Strength Ω	Collision Strength Data Source
$^3P_1-{}^3P_0$	2.425×10^5	E	1.3×10^{-3}	G1	0.244	SSS
$^3P_2-{}^3P_0$	90082.0	E	5.2×10^{-9}	G1	0.122	SSS
$^1D_2-{}^3P_0$	3301.3	E	1.9×10^{-5}	G1	0.153	SSS
$^1S_0-{}^3P_0$	1564.6	E	0.0	...	0.024	SSS
$^3P_2-{}^3P_1$	1.433×10^5	E	4.6×10^{-3}	G1	0.578	SSS
$^1D_2-{}^3P_1$	3346.8	E	0.138	G1	0.460	SSS
$^1S_0-{}^3P_1$	1574.8	E	4.2	G1	0.073	SSS
$^1D_2-{}^3P_2$	3426.8	E	0.38	G1	0.767	SSS
$^1S_0-{}^3P_2$	1592.3	E	6.8×10^{-3}	G1	0.121	SSS
$^1S_0-{}^1D_2$	2974.2	E	2.60	G1	0.185	SSS

TABLE 1I

ION Mg V; CONFIGURATION $2p^4$

Transition	Wavelength λ(Å)	Wavelength Data Source	Transition Probability $A(s^{-1})$	Transition Probability Data Source	Collision Strength Ω	Collision Strength Data Source
$^3P_1-{}^3P_2$	56053.8	E	0.125	MB	0.400	SSS
$^3P_0-{}^3P_2$	39611.8	E	8.8×10^{-7}	MB	0.0908	SSS
$^1D_2-{}^3P_2$	2784.0	E	1.96	MB	0.541	SSS
$^1S_0-{}^3P_2$	1293.9	E	0.027	MB	0.081	SSS
$^3P_0-{}^3P_1$	1.350×10^5	E	0.022	MB	0.1558	SSS
$^1D_2-{}^3P_1$	2929.5	E	0.56	MB	0.324	SSS
$^1S_0-{}^3P_1$	1324.4	E	23.0	MB	0.049	SSS
$^1D_2-{}^3P_0$	2994.5	E	6.7×10^{-5}	MB	0.108	SSS
$^1S_0-{}^3P_0$	1337.5	E	0.0	...	0.016	SSS
$^1S_0-{}^1D_2$	2417.2	E	4.2	MB	0.129	SSS

TABLE 1J

ION Mg VI; CONFIGURATION $2p^3$

Transition	Wavelength λ(Å)	Wavelength Data Source	Transition Probability $A(s^{-1})$	Transition Probability Data Source	Collision Strength Ω	Collision Strength Data Source
$^2D_{5/2}-{}^4S_{3/2}$	1806.5	E	0.0054	G1	0.391	SSS
$^2D_{3/2}-{}^4S_{3/2}$	1805.9	E	0.12	G1	0.261	SSS
$^2P_{1/2}-{}^4S_{3/2}$	1191.6	E	5.3	G1	0.096	SSS
$^2P_{3/2}-{}^4S_{3/2}$	1190.1	E	13.0	G1	0.193	SSS
$^2D_{3/2}-{}^2D_{5/2}$	5.587×10^6	E	1.5×10^{-7}	G1	0.560	I[a]
$^2P_{1/2}-{}^2D_{5/2}$	3500.9	E	0.15	G1	0.167	I[a]
$^2P_{3/2}-{}^2D_{5/2}$	3488.1	E	2.4	G1	0.428	I[a]
$^2P_{1/2}-{}^2D_{3/2}$	3503.1	E	2.5	G1	0.149	I[a]
$^2P_{3/2}-{}^2D_{3/2}$	3490.3	E	3.8	G1	0.226	I[a]
$^2P_{3/2}-{}^2P_{1/2}$	9.551×10^5	E	1.6×10^{-5}	G1	0.203	B

[a] I: Interpolated values using data given by SSS and CAE.

TABLE 1K

ION Mg VII; CONFIGURATION $2p^2$

Transition	Wavelength λ(Å)	Wavelength Data Source	Transition Probability $A(s^{-1})$	Transition Probability Data Source	Collision Strength Ω	Collision Strength Data Source
$^{3}P_{1}-{}^{3}P_{0}$	89501.5	E	0.026	N	0.156	I[a]
$^{3}P_{2}-{}^{3}P_{0}$	34102.9	E	2.4×10^{-7}	N	0.080	I[a]
$^{1}D_{2}-{}^{3}P_{0}$	2441.2	E	1.6×10^{-4}	N	0.089	SSS
$^{1}S_{0}-{}^{3}P_{0}$	1174.1	E	0.0	...	0.014	SSS
$^{3}P_{2}-{}^{3}P_{1}$	55096.4	E	0.080	N	0.378	I[a]
$^{1}D_{2}-{}^{3}P_{1}$	2509.7	E	1.05	N	0.267	SSS
$^{1}S_{0}-{}^{3}P_{1}$	1189.7	E	34.5	N	0.043	SSS
$^{1}D_{2}-{}^{3}P_{2}$	2629.5	E	2.75	N	0.444	SSS
$^{1}S_{0}-{}^{3}P_{2}$	1216.0	E	0.035	N	0.071	SSS
$^{1}S_{0}-{}^{1}D_{2}$	2261.9	E	4.07	N	0.123	SSS

[a] I: Interpolated values using data given by B and CAE and with infinite limits given by SSS.

TABLE 1L

ION Si VII; CONFIGURATION $2p^4$

Transition	Wavelength λ(Å)	Wavelength Data Source	Transition Probability $A(s^{-1})$	Transition Probability Data Source	Collision Strength Ω	Collision Strength Data Source
$^{3}P_{1}-{}^{3}P_{2}$	24815.1	E	1.45	MB	0.317	I*[a]
$^{3}P_{0}-{}^{3}P_{2}$	17959.8	E	1.82×10^{-5}	MB	0.064	I*[a]
$^{1}D_{2}-{}^{3}P_{2}$	2147.8	E	12.9	MB	0.386	I[b]
$^{1}S_{0}-{}^{3}P_{2}$	1006.7	E	0.105	MB	0.060	I[b]
$^{3}P_{0}-{}^{3}P_{1}$	65011.1	E	0.194	MB	0.126	I*[a]
$^{1}D_{2}-{}^{3}P_{1}$	2351.3	E	3.3	MB	0.231	I[b]
$^{1}S_{0}-{}^{3}P_{1}$	1049.3	E	148.0	MB	0.036	I[b]
$^{1}D_{2}-{}^{3}P_{0}$	2439.5	E	2.5×10^{-4}	MB	0.077	I[b]
$^{1}S_{0}-{}^{3}P_{0}$	1066.5	E	0.0	...	0.012	I[b]
$^{1}S_{0}-{}^{1}D_{2}$	1894.8	E	5.5	MB	0.094	I[b]

[a] I*: Interpolated values using data in B and CAE, and with infinite limits given by SSS.
[b] I: Interpolated values using data given by SSS and CAE.

TABLE 1M

ION Si VIII; CONFIGURATION $2p^3$

Transition	Wavelength λ(Å)	Wavelength Data Source	Transition Probability $A(s^{-1})$	Transition Probability Data Source	Collision Strength Ω	Collision Strength Data Source
$^{2}D_{3/2}-{}^{4}S_{3/2}$	1445.8	E	1.6066	G2	0.168	I[a]
$^{2}D_{5/2}-{}^{4}S_{3/2}$	1440.6	E	0.046	G2	0.252	I[a]
$^{2}P_{1/2}-{}^{4}S_{3/2}$	949.2	E	31.0	G2	0.061	I[a]
$^{2}P_{3/2}-{}^{4}S_{3/2}$	944.4	E	75.0	G2	0.123	I[a]
$^{2}D_{5/2}-{}^{2}D_{3/2}$	4.040×10^{5}	E	1.6×10^{-4}	G2	0.347	I[a]
$^{2}P_{1/2}-{}^{2}D_{3/2}$	2763.9	E	13.34	G2	0.098	I[a]
$^{2}P_{3/2}-{}^{2}D_{3/2}$	2723.6	E	22.17	G2	0.161	I[a]
$^{2}P_{1/2}-{}^{2}D_{5/2}$	2782.9	E	0.22	G2	0.114	I[a]
$^{2}P_{3/2}-{}^{2}D_{5/2}$	2742.1	E	12.42	G2	0.296	I[a]
$^{2}P_{3/2}-{}^{2}P_{1/2}$	1.868×10^{5}	E	1.3×10^{-3}	G2	0.139	I*[b]

[a] I: Interpolated values using data from SSS and CAE.
[b] I*: Interpolated value using data from B and CAE, and with infinite limit given by SSS.

TABLE 1N

Ion Si IX; Configuration $2p^2$

Transition	Wavelength λ(Å)	Wavelength Data Source	Transition Probability $A(s^{-1})$	Transition Probability Data Source	Collision Strength Ω	Collision Strength Data Source
$^3P_1-{}^3P_0$...........	39169.6	E	0.312	N	0.101	B
$^3P_2-{}^3P_0$...........	15581.2	E	5.5×10^{-6}	N	0.0523	B
$^1D_2-{}^3P_0$..........	1889.0	E	6.6×10^{-4}	N	0.056	I[a]
$^1S_0-{}^3P_0$...........	927.4	E	0.0	...	0.009	I[a]
$^3P_2-{}^3P_1$...........	25873.2	E	0.767	N	0.244	B
$^1D_2-{}^3P_1$..........	1984.7	E	6.72	N	0.169	I[a]
$^1S_0-{}^3P_1$...........	949.9	E	197.0	N	0.027	I[a]
$^1D_2-{}^3P_2$..........	2149.6	E	15.8	N	0.282	I[a]
$^1S_0-{}^3P_2$...........	986.1	E	0.141	N	0.044	I[a]
$^1S_0-{}^1D_2$..........	1821.9	E	5.10	N	0.084	I[a]

[a] I: Interpolated values using data given by SSS and CAE.

TABLE 1O

Ion S II; Configuration $3p^3$

Transition	Wavelength Λ(Å)	Wavelength Data Source	Transition Probability $A(s^{-1})$	Transition Probability Data Source	Collision Strength Ω	Collision Strength Data Source
$^2D_{3/2}-{}^4S_{3/2}$...........	6730.8	G1	1.8×10^{-3}	G1	1.229	KC
$^2D_{5/2}-{}^4S_{3/2}$...........	6716.4	G1	4.7×10^{-4}	G1	1.843	KC
$^2P_{1/2}-{}^4S_{3/2}$...........	4076.4	G1	0.134	G1	0.494	KC
$^2P_{3/2}-{}^4S_{3/2}$...........	4068.6	G1	0.34	G1	0.987	KC
$^2D_{5/2}-{}^2D_{3/2}$..........	3.144×10^5	WSG2	3.3×10^{-7}	G1	2.558	KC
$^2P_{1/2}-{}^2D_{3/2}$..........	10338.8	G1	0.20	G1	1.727	KC
$^2P_{3/2}-{}^2D_{3/2}$..........	10287.1	G1	0.17	G1	2.194	KC
$^2P_{1/2}-{}^2D_{5/2}$..........	10372.6	G1	0.087	G1	1.541	KC
$^2P_{3/2}-{}^2D_{5/2}$..........	10320.6	G1	0.21	G1	4.323	KC
$^2P_{3/2}-{}^2P_{1/2}$..........	2.141×10^6	WSG2	1.0×10^{-6}	G1	0.796	KC

TABLE 1P

Ion S III; Configuration $3p^2$

Transition	Wavelength λ(Å)	Wavelength Data Source	Transition Probability $A(s^{-1})$	Transition Probability Data Source	Collision Strength Ω	Collision Strength Data Source
$^3P_1-{}^3P_0$...........	3.364×10^5	WSG2	4.7×10^{-4}	G1	1.215	KC
$^3P_2-{}^3P_0$...........	1.201×10^5	WSG2	4.7×10^{-8}	G1	0.569	KC
$^1D_2-{}^3P_0$..........	8831.5	G1	9.1×10^{-6}	G1	0.548	KC
$^1S_0-{}^3P_0$...........	3681.1	G1	0.0	...	0.114	KC
$^3P_2-{}^3P_1$...........	1.868×10^5	WSG2	2.4×10^{-3}	G1	2.797	KC
$^1D_2-{}^3P_1$..........	9069.4	G1	0.025	G1	1.643	KC
$^1S_0-{}^3P_1$...........	3721.7	G1	0.85	G1	0.342	KC
$^1D_2-{}^3P_2$..........	9532.1	G1	0.064	G1	2.738	KC
$^1S_0-{}^3P_2$...........	3796.7	G1	0.016	G1	0.569	KC
$^1S_0-{}^1D_2$..........	6312.1	G1	2.54	G1	1.28	KC

TABLE 1Q

Ion S IX; Configuration $2p^4$

Transition	Wavelength λ(Å)	Wavelength Data Source	Transition Probability $A(s^{-1})$	Transition Probability Data Source	Collision Strength Ω	Collision Strength Data Source
$^3P_1-^3P_2$	12520.3	E	11.4	MB	0.218	CAE
$^3P_0-^3P_2$	9402.0	E	2.2×10^{-4}	MB	0.045	CAE
$^1D_2-^3P_2$	1715.1	E	65.0	MB	0.275	CAE
$^1S_0-^3P_2$	815.1	E	0.33	MB	0.043	CAE
$^3P_0-^3P_1$	37750.1	E	0.95	MB	0.092	CAE
$^1D_2-^3P_1$	1987.4	E	14.2	MB	0.164	CAE
$^1S_0-^3P_1$	871.8	E	710.0	MB	0.025	CAE
$^1D_2-^3P_0$	2097.8	E	7.6×10^{-4}	MB	0.054	CAE
$^1S_0-^3P_0$	892.4	E	0.0	...	0.008	CAE
$^1S_0-^1D_2$	1553.2	E	6.9	MB	0.071	CAE

TABLE 1R

Ion S X; Configuration $2p^3$

Transition	Wavelength λ(Å)	Wavelength Data Source	Transition Probability $A(s^{-1})$	Transition Probability Data Source	Collision Strength Ω	Collision Strength Data Source
$^2D_{3/2}-^4S_{3/2}$	1213.6	E	15.021	G2	0.112	CAE
$^2D_{5/2}-^4S_{3/2}$	1196.9	E	0.374	G2	0.170	CAE
$^2P_{1/2}-^4S_{3/2}$	787.8	E	140.005	G2	0.041	CAE
$^2P_{3/2}-^4S_{3/2}$	776.6	E	320.001	G2	0.083	CAE
$^2D_{5/2}-^2D_{3/2}$	86956.5	E	0.016	G2	0.231	CAE
$^2P_{1/2}-^2D_{3/2}$	2245.1	E	57.47	G2	0.071	CAE
$^2P_{3/2}-^2D_{3/2}$	2156.5	E	100.26	G2	0.117	CAE
$^2P_{1/2}-^2D_{5/2}$	2304.6	E	0.29	G2	0.083	CAE
$^2P_{3/2}-^2D_{5/2}$	2211.4	E	54.59	G2	0.210	CAE
$^2P_{3/2}-^2P_{1/2}$	54644.8	E	0.052	G2	0.094	CAE

TABLE 1S

Ion S XI; Configuration $2p^2$

Transition	Wavelength λ(Å)	Wavelength Data Source	Transition Probability $A(s^{-1})$	Transition Probability Data Source	Collision Strength Ω	Collision Strength Data Source
$^3P_1-^3P_0$	19135.1	E	2.72	N	0.068	CAE
$^3P_2-^3P_0$	8069.1	E	7.7×10^{-5}	N	0.033	CAE
$^1D_2-^3P_0$	1489.1	E	2.4×10^{-3}	N	0.039	CAE
$^1S_0-^3P_0$	752.0	E	0.0	...	0.006	CAE
$^3P_2-^3P_1$	13952.8	E	4.74	N	0.160	CAE
$^1D_2-^3P_1$	1614.8	E	33.6	N	0.117	CAE
$^1S_0-^3P_1$	782.8	E	824.0	N	0.018	CAE
$^1D_2-^3P_2$	1826.2	E	69.5	N	0.195	CAE
$^1S_0-^3P_2$	829.3	E	0.460	N	0.030	CAE
$^1S_0-^1D_2$	1519.2	E	5.71	N	0.059	CAE

TABLE 1T

ION Fe XI; CONFIGURATION $3p^4$

Transition	Wavelength λ(Å)	Wavelength Data Source	Transition Probability $A(s^{-1})$	Transition Probability Data Source	Collision Strength Ω	Collision Strength Data Source
$^3P_1-^3P_2$	7891.8	SW	43.0	SW	0.270	KC
$^3P_0-^3P_2$	6925.0	M	1.21×10^{-2}	MB	0.086	KC
$^1D_2-^3P_2$	2649.0	SW	91.0	SW	0.131	KC
$^1S_0-^3P_2$	1243.3	SW	1.9	SW	0.016	KC
$^3P_0-^3P_1$	56433.4	M	0.28	MB	0.060	KC
$^1D_2-^3P_1$	3986.8	SW	9.3	SW	0.079	KC
$^1S_0-^3P_1$	1467.0	SW	910.0	SW	0.009	KC
$^1D_2-^3P_0$	4291.3	M	1.68×10^{-3}	MB	0.026	KC
$^1S_0-^3P_0$	1518.0	M	0.0	...	0.003	KC
$^1S_0-^1D_2$	2341.8	SW	9.3	SW	0.342	KC

TABLE 1U

ION Fe XII; CONFIGURATION $3p^3$

Transition	Wavelength λ(Å)	Wavelength Data Source	Transition Probability $A(s^{-1})$	Transition Probability Data Source	Collision Strength Ω	Collision Strength Data Source
$^2D_{3/2}-^4S_{3/2}$	2406.0	SW	53.048	G2	0.063	KC
$^2D_{5/2}-^4S_{3/2}$	2170.0	SW	2.22	G2	0.095	KC
$^2P_{1/2}-^4S_{3/2}$	1349.6	SW	190.13	G2	0.016	KC
$^2P_{3/2}-^4S_{3/2}$	1242.2	SW	340.01	G2	0.032	KC
$^2D_{5/2}-^2D_{3/2}$	22100.0	SW	0.87	G2	0.141	KC
$^2P_{1/2}-^2D_{3/2}$	3072.0	SW	69.91	G2	0.308	KC
$^2P_{3/2}-^2D_{3/2}$	2568.0	SW	200.72	G2	0.332	KC
$^2P_{1/2}-^2D_{5/2}$	3568.0	SW	0.33	G2	0.218	KC
$^2P_{3/2}-^2D_{5/2}$	2903.0	SW	79.4	G2	0.729	KC
$^2P_{3/2}-^2P_{1/2}$	15600.0	SW	2.0	G2	0.058	KC

TABLE 1V

ION Fe XIII; CONFIGURATION $3p^2$

Transition	Wavelength λ(Å)	Wavelength Data Source	Transition Probability $A(s^{-1})$	Transition Probability Data Source	Collision Strength Ω	Collision Strength Data Source
$^3P_1-^3P_0$	10746.8	SW	14.0	SW	0.046	KC
$^3P_2-^3P_0$	5387.0	M	6.1×10^{-3}	MB	0.063	KC
$^1D_2-^3P_0$	2080.4	M	4.1×10^{-3}	MB	0.019	KC
$^1S_0-^3P_0$	1219.0	M	0.0	...	0.002	KC
$^3P_2-^3P_1$	10797.9	SW	9.7	SW	0.267	KC
$^1D_2-^3P_1$	2580.0	SW	69.0	SW	0.058	KC
$^1S_0-^3P_1$	1213.0	SW	1150.0	SW	0.007	KC
$^1D_2-^3P_2$	3388.5	SW	84.0	SW	0.097	KC
$^1S_0-^3P_2$	1366.5	SW	4.9	SW	0.012	KC
$^1S_0-^1D_2$	2288.9	SW	9.2	SW	0.343	KC

SOURCE.—B, Blaha 1968. CAE, Czyzak, Aller, and Euwema 1974. CKMSS, Czyzak *et al.* 1968. E, Edlén 1972. G1, Garstang 1968. G2, Garstang 1972. KC, Krueger and Czyzak 1970. MB, Malville and Berger 1965. M, Moore 1971. N, Nussbaumer 1971. O, Osterbrock 1974. SSS, Saraph, Seaton, and Shemming 1968. SW, Smith and Wiese 1973. WSG1, Wiese, Smith, and Glennon 1966*a*. WSG2, Wiese, Smith, and Glennon 1966*b*. I, Interpolated values as explained under the relevant tables.

TABLE 2

$q = 1, 5$ CONFIGURATIONS

Ion	Configuration	Transition	Wavelength λ(Å)	Wavelength Data Source	Transition Probability $A(\mathrm{s}^{-1})$	Transition Probability Data Source	Collision Strength Ω	Collision Strength Data Source
C II	$2p$	$^2P_{3/2}-^2P_{1/2}$	1.56×10^6	G1	2.4×10^{-6}	G1	1.432	SSS
N III	$2p$	$^2P_{3/2}-^2P_{1/2}$	5.73×10^5	G1	4.8×10^{-5}	G1	1.097	SSS
O IV	$2p$	$^2P_{3/2}-^2P_{1/2}$	2.59×10^5	G1	5.2×10^{-4}	G1	0.810	SSS
Ne II	$2p^5$	$^2P_{1/2}-^2P_{3/2}$	1.28×10^5	G1	0.0086	G1	0.244	SSS
Ne VI	$2p$	$^2P_{3/2}-^2P_{1/2}$	76320.0	WSG1	0.0202	WSG1	0.433	SSS
Mg IV	$2p^5$	$^2P_{1/2}-^2P_{3/2}$	44900.0	G1	0.20	G1	0.300	SSS
Mg VIII	$2p$	$^2P_{3/2}-^2P_{1/2}$	30258.0	WSG1	0.324	WSG1	0.20	G(comm.)
Si II	$3p$	$^2P_{3/2}-^2P_{1/2}$	3.48×10^5	G1	2.1×10^{-4}	G1	3.780	B
Si VI	$2p^5$	$^2P_{1/2}-^2P_{3/2}$	19603.0	WSG2	2.38	WSG2	0.242	SSS
Si X	$2p$	$^2P_{3/2}-^2P_{1/2}$	14302.0	WSG2	3.07	WSG2	0.170	B
S IV	$3p$	$^2P_{3/2}-^2P_{1/2}$	1.06×10^5	G1	0.0077	G1	1.670	KC
S VIII	$2p^5$	$^2P_{1/2}-^2P_{3/2}$	9917.9	WSG2	18.6	WSG2	0.174	CAE
S XII	$2p$	$^2P_{3/2}-^2P_{1/2}$	7536.0	CAE	20.817	CAE	0.117	CAE
Fe X	$3p^5$	$^2P_{1/2}-^2P_{3/2}$	6374.5	CAE	69.149	CAE	0.286	KC
Fe XIV	$3p$	$^2P_{3/2}-^2P_{1/2}$	5302.9	CAE	60.056	CAE	0.195	KC

SOURCE.— B, Blaha 1968. CAE, Czyzak, Aller, and Euwema 1974. G1, Garstang 1968. KC, Krueger and Czyzak 1970. SSS, Saraph, Seaton, and Shemming 1968. WSG1, Wiese, Smith, and Glennon 1966*a*. WSG2, Wiese, Smith, and Glennon 1966*b*.

It is particularly useful to summarize the various collision strengths, because the collision strengths sources in the literature are numerous. Moreover, if the Z-dependence of the collision strengths is given, unknown values for different Z's can be interpolated. The best way to summarize the collision strengths is to plot $Z^2\Omega$ versus Z^{-1} along the isoelectronic sequence. The reason for this is that as the charge Z tends to infinity, $Z^2\Omega$ remains finite (Saraph, Seaton, and Shemming 1968). The infinite Z limit is given in Saraph, Seaton, and Shemming (1968) and, therefore, interpolations can be carried out. We should point out that considerable effort has been spent by various workers on calculating resonances. These resonances are significant at particular energies but less significant when averaged over a Maxwellian distribution of the electrons. This average suffices for most astrophysical cases (Garstang, private communication). Generally, as Z increases the calculations become more reliable. We found that the $Z^2\Omega$'s are fairly smooth functions of Z^{-1}. The accuracy of our interpolations was checked by taking the interpolated values of some forbidden transitions and using the sum rules to arrive at a total collision strength for transitions from the upper to the lower levels. This value was then compared to the published value. In the cases where this was done, satisfactory agreement resulted (within a few percent agreement).

For the neutral ions N I and O I the collision strengths are temperature dependent. We fitted the collision strengths in Kaplan and Pikelner (1970) and Osterbrock (1974) to a $T^{1/2}$ function in all cases. The results obtained agreed within 10% of the actual data. The sum rules were used when needed.

In Figures 1–7 the $Z^2\Omega$'s along isoelectronic sequences as a function of Z^{-1} are plotted. The references for the various collision strengths through which the curves were drawn are given in Tables 1A–1V. In Figure 1, the C I ($2p^2$) sequence collision strengths are shown. The index "1", "2", and "3" refers to the ^3P, ^1D, and ^1S multiplets respectively. In Figure 2, the fine structure collision strengths for the C I sequence are given. In Figure 3, the N I ($2p^3$) sequence collision strengths are shown. The index "1", "2", and "3" refers to the multiplets ^4S, ^2D, and ^2P respectively. In Figure 4 and 5 the collision strengths between the various levels of the multiplets ^2D and ^2P are shown. Finally, in Figures 6 and 7 the collision strengths for the O I ($2p^4$) sequence are shown. Those figures are analogous to Figures 1 and 2.

III. RESULTS AND CONCLUSIONS

Using the data discussed in the previous section we now turn our attention to the results of our computations.

a) *Relative Populations of the Various Levels*

The relative populations N_j's are computed by using the formulae of the Appendix and the data of § II. The expressions for the N_j can be found in the system of equations (A4).

We made the assumption that allowed transitions from higher levels do not populate the ground state levels. In other words, we only considered transitions between these levels. This is probably a good assumption since the

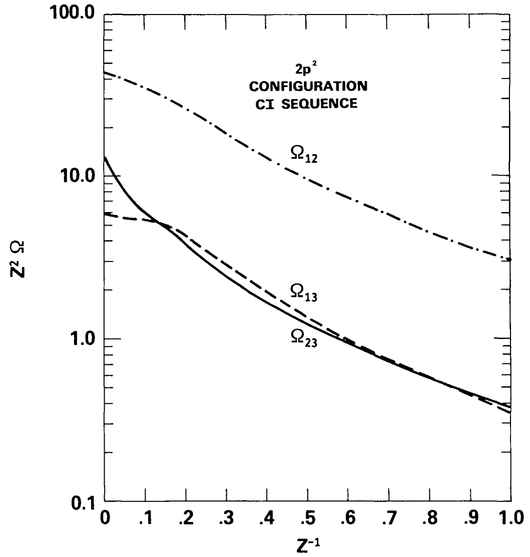

FIG. 1.—C I isoelectronic collision strengths. Indexes "1", "2", and "3" refer to the ^3P, ^1D, and ^1S multiplets, respectively.

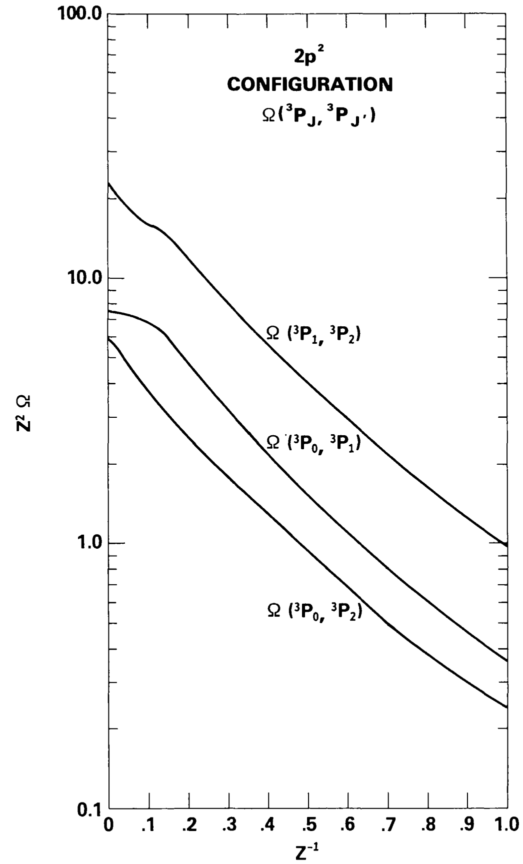

FIG. 2.—C I sequence collision strengths for fine structure transitions.

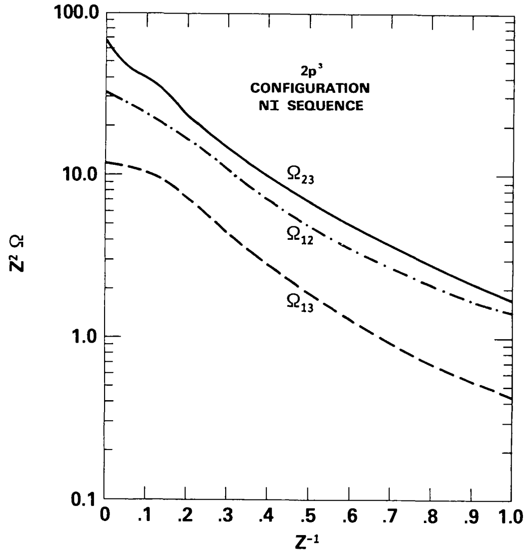

FIG. 3.—N I sequence collision strengths. The indexes "1", "2", and "3" refer to the ^4S, ^2D, and ^2P multiplets, respectively.

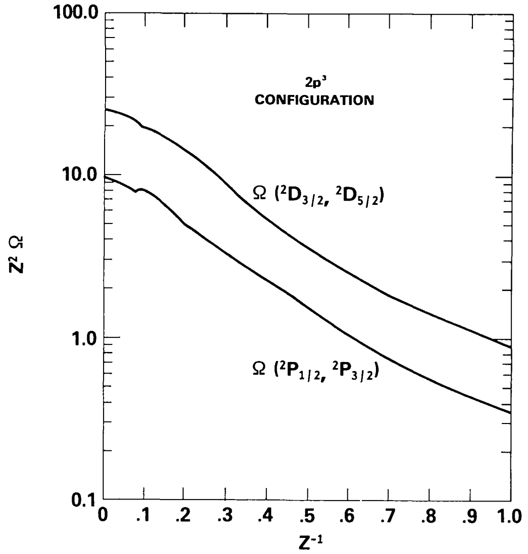

FIG. 4.—Collision strengths for fine structure transitions in the N I sequence.

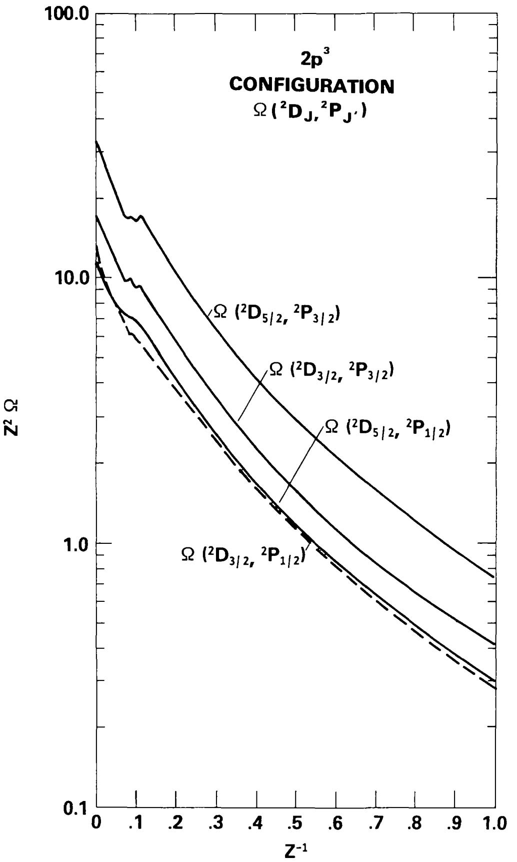

FIG. 5.—Collision strengths between the various levels of the ^{2}D and ^{2}P multiplets in the N I sequence.

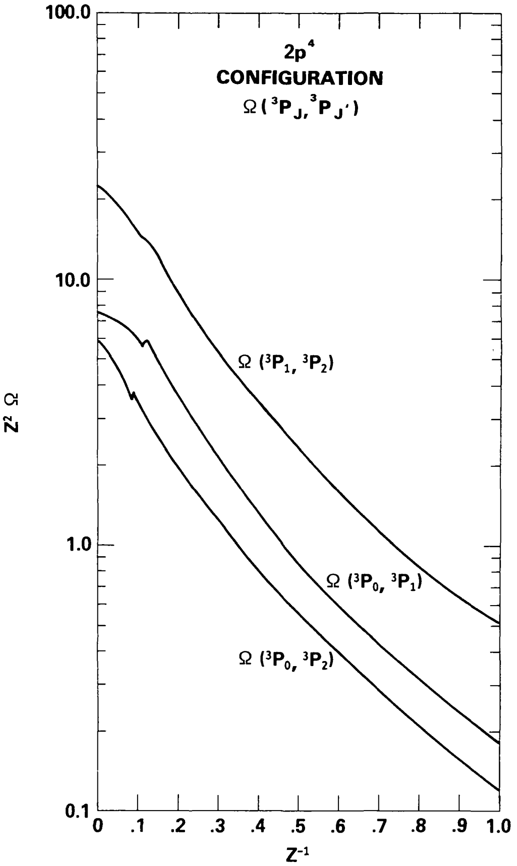

FIG. 7.—O I sequence, analogous to Fig. 2.

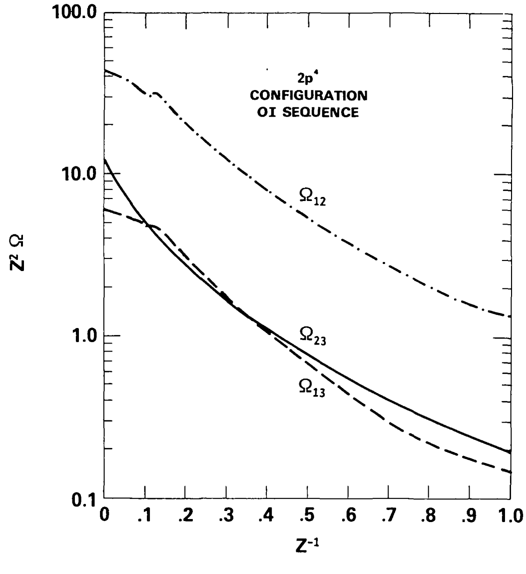

FIG. 6.—O I sequence, analogous to Fig. 1.

energy differences between levels which are connected via allowed transitions are much greater (say, by factors around 5–10) than the energy differences between the ground state levels. The relative populations of the higher levels depend on the collisional excitation rates from the lower levels which are proportional to $\exp(-\Delta E/kT)$. Due to the existence of this factor, collisional population of levels which can give allowed transitions to the ground state levels is negligible except at high temperatures—at which the relevant ion becomes ionized anyway (see also Mewe 1972). Likewise, we ignored allowed transitions to the ground levels from higher levels which themselves are populated from recombinations.

The relative populations N_j, $j=2,3,4,5$ for $q=2,3$, 4 ions are shown in Tables 3A–3V: N I, Table 3A; N II, 3B; O I, 3C; O II, 3D; O III, 3E; Ne III, 3F; Ne IV, 3G; Ne V, 3H; Mg V, 3I; Mg VI, 3J; Mg VII, 3K; Si VII, 3L; Si VIII, 3M; Si IX, 3N; S II, 3O; S III, 3P; S IX, 3Q; S X, 3R; S XI, 3S; Fe XI, 3T; Fe XII, 3U; Fe XIII, 3V. The relative population N_2 for $q=1,5$ ions is shown in Tables 4A–4O: C II, Table 4A; N III, 4B; O IV, 4C; Ne II, 4D; Ne VI, 4E; Mg IV, 4F; Mg VIII, 4G; Si II, 4H; Si VI, 4I; Si X, 4J; S IV, 4K; S VIII, 4L; S XII, 4M; Fe X, 4N; Fe XIV, 4O. In each of the above tables the relative populations are given for different densities n, where n is the total number density of hydrogen and helium nuclei, and for four different temperatures T. We present the results as a function of n rather than n_e because the electron number density would vary as the gas recombined under different conditions and could not be used as a general parameter. Below $T \approx 10^4$ K the results are strictly correct for a gas that is cooling radiatively, although the results should also apply with satisfactory agreement to cases where there is no time variation (like H II regions) of the electron density. On the other hand, our results apply generally for $T \gtrsim 10^4$ K independently of the ionizing process. The temperature range was chosen so that the relevant ionic abundance was above ~5%. Time dependent radiative cooling of the gas was assumed for the values of the ionic abundances (Kafatos 1973; Shapiro and Moore 1976). Since specific ions persist over a larger temperature range in the time-dependent case compared to the steady-state (in which recombinations balance collisional ionizations), the temperature ranges given in Tables 3A–3V and Tables 4A–4O should be adequate for most purposes. If the N_j's are desired outside the temperature ranges given in the tables, extrapolation can be performed using the tabulated values.

We have not tabulated the values of N_1 since they can be easily found from the requirement that the sum of all N_j's is equal to one.

b) *Line Ratios*

Ratios of lines of the same ion can be used to determine the density or temperature of the cosmic gas.

For ions with ground state configuration $q=3$, the line intensity ratio $I(^2D_{5/2}-{}^4S_{3/2})/I(^2D_{3/2}-{}^4S_{3/2})$ shows strong density dependence for the following reason: if an ion has two energy levels close to each other, then the ratio

TABLE 3A

ION N I; CONFIGURATION $2p^3$

Density (cm^{-3})[a]	RELATIVE POPULATIONS – Log(N_j)			
Log(n)	N_2	N_3	N_4	N_5
	a) Log $T=4.1$			
0........	3.8706	4.4096	9.1597	8.8838
2........	1.9227	2.4089	7.0852	6.8480
4........	0.9060	1.1082	4.6079	4.5443
6........	0.8566	1.0401	2.6573	2.5376
8........	0.8980	1.0755	1.8820	1.5876
10........	0.9019	1.0784	1.8558	1.5548
	b) Log $T=3.9$			
0........	4.5250	5.0657	10.1069	9.8309
2........	2.5638	3.0614	8.0430	7.7985
4........	1.4232	1.6284	5.5162	5.4468
6........	1.3469	1.5273	3.5218	3.4105
8........	1.3647	1.5421	2.6346	2.3418
10........	1.3669	1.5437	2.5982	2.2973
	c) Log $T=3.8$			
0........	4.9834	5.5249	10.7805	10.5045
2........	3.0163	3.5206	8.7249	8.4760
4........	1.8160	2.0249	6.1931	6.1198
6........	1.7248	1.9041	4.1734	4.0679
8........	1.7344	1.9119	3.2081	2.9167
10........	1.7360	1.9130	3.1627	2.8618
	d) Log $T=3.7$			
0........	5.5547	6.0970	11.6307	11.3546
2........	3.5819	4.0932	9.5844	9.3309
4........	2.3196	2.5343	7.0599	6.9818
6........	2.2111	2.3900	5.0124	4.9136
8........	2.2152	2.3927	3.9479	3.6589
10........	2.2162	2.3934	3.8881	3.5873

[a] The density $n=n_{\mathrm{H}}+n_{\mathrm{He}}$ (n is the total number density of hydrogen and helium nuclei).

TABLE 3B

ION N II; CONFIGURATION $2p^2$

Density(cm^{-3})[a]	RELATIVE POPULATIONS – Log(N_j)			
Log(n)	N_2	N_3	N_4	N_5
	a) Log $T=4.9$			
0...........	1.8343	2.6729	5.6387	9.2119
2...........	0.3433	0.7709	3.6387	7.2114
4...........	0.5044	0.2331	1.6690	5.1966
6...........	0.6212	0.3882	0.5620	3.0620
8...........	0.6447	0.4240	0.5338	1.5430
10...........	0.6481	0.4269	0.5459	1.3834
	b) Log $T=4.5$			
0...........	1.6903	2.5500	5.6353	9.4030
2...........	0.3218	0.6816	3.6348	7.4017
4...........	0.4989	0.2424	1.6762	5.3751
6...........	0.5787	0.3527	0.6879	3.2099
8...........	0.5903	0.3701	0.6657	1.8244
10...........	0.5914	0.3712	0.6707	1.7138
	c) Log $T=4.1$			
0...........	1.5788	2.4758	5.9229	10.1947
2...........	0.3152	0.6325	3.9209	8.1916
4...........	0.4814	0.2557	1.9731	6.1456
6...........	0.5139	0.2945	1.0765	3.9424
8...........	0.5166	0.2988	1.0507	2.6897
10...........	0.5167	0.2989	1.0515	2.6122
	d) Log $T=3.7$			
0...........	1.5295	2.4540	6.9793	12.5419
2...........	0.3143	0.6193	4.9734	10.5346
4...........	0.4667	0.2653	3.0300	8.4735
6...........	0.4751	0.2634	2.1771	6.2525
8...........	0.4753	0.2636	2.1499	5.0712
10...........	0.4753	0.2636	2.1497	5.0070

[a] The density $n=n_{\mathrm{H}}+n_{\mathrm{He}}$ (n is the total number density of hydrogen and helium nuclei).

TABLE 3C

Ion O I; Configuration $2p^4$

Density(cm^{-3})[a]	Relative Populations – Log(N_j)			
Log(n)	N_2	N_3	N_4	N_5
a) Log T=4.0				
0	4.4168	4.3782	7.2290	11.6749
2	2.4244	2.4010	5.2289	9.6748
4	0.7759	1.1263	3.2309	7.6686
6	0.5024	0.9880	1.5434	5.5253
8	0.5067	0.9882	1.2645	3.5852
10	0.5069	0.9883	1.2627	3.0867
b) Log T=3.9				
0	4.5020	4.4700	7.5534	12.2849
2	2.5081	2.4883	5.5533	10.2848
4	0.8170	1.1448	3.5541	8.2786
6	0.4972	0.9813	1.8281	6.1401
8	0.4972	0.9798	1.5107	4.1674
10	0.4973	0.9798	1.5071	3.6225
c) Log T=3.8				
0	4.6129	4.5957	7.9648	13.0556
2	2.6176	2.6094	5.9647	11.0555
4	0.8768	1.1787	3.9643	9.0495
6	0.4955	0.9787	2.1951	6.9216
8	0.4918	0.9757	1.8261	4.9116
10	0.4918	0.9757	1.8207	4.3026
d) Log T=3.7				
0	4.7598	4.7720	8.4852	14.0268
2	2.7630	2.7812	6.4852	12.0267
4	0.9658	1.2386	4.4838	10.0211
6	0.4976	0.9804	2.6672	7.9095
8	0.4899	0.9756	2.2268	5.8591
10	0.4899	0.9755	2.2193	5.1621

[a] The density $n=n_{\mathrm{H}}+n_{\mathrm{He}}$.

TABLE 3D

Ion O II; Configuration $2p^3$

Density(cm^{-3})[a]	Relative Populations – Log(N_j)			
Log(n)	N_2	N_3	N_4	N_5
a) Log T=5.0				
0	3.9834	4.6952	8.3101	8.5034
2	1.9967	2.6965	6.3025	6.4972
4	0.5826	0.9218	4.1216	4.3268
6	0.4403	0.6019	2.0637	2.2642
8	0.5235	0.6973	0.8699	1.1585
10	0.5399	0.7161	0.8021	1.1030
b) Log T=4.6				
0	4.0554	4.7704	8.4933	8.6867
2	2.0718	2.7692	6.4785	6.6740
4	0.6969	0.9962	4.1919	4.3953
6	0.5492	0.7142	2.1158	2.3207
8	0.5983	0.7734	1.0441	1.3369
10	0.6051	0.7814	0.9953	1.2963

TABLE 3D—*Continued*

Density(cm^{-3})[a]	Relative Populations – Log(N_j)			
Log(n)	N_2	N_3	N_4	N_5
c) Log T=4.1				
0	4.7667	5.4891	9.6330	9.8263
2	2.7856	3.4818	7.6043	7.8009
4	1.3953	1.6658	5.1416	5.3436
6	1.2077	1.3812	3.0278	3.2402
8	1.2063	1.3831	2.0931	2.3893
10	1.2064	1.3835	2.0596	2.3607
d) Log T=3.7				
0	6.6928	7.4204	12.5609	12.7543
2	4.7138	5.4112	10.5263	10.7234
4	3.3405	3.6059	8.0207	8.2225
6	3.1573	3.3364	5.9167	6.1331
8	3.1544	3.3329	5.0544	5.3515
10	3.1543	3.3329	5.0269	5.3280

[a] The density $n=n_{\mathrm{H}}+n_{\mathrm{He}}$.

TABLE 3E

Ion O III; Configuration $2p^2$

Density(cm^{-3})[a]	Relative Populations – Log(N_j)			
Log(n)	N_2	N_3	N_4	N_5
a) Log T=5.3				
0	3.1757	4.0743	6.7319	9.5167
2	1.2113	2.0739	4.7319	7.5164
4	0.3364	0.4196	2.7337	5.5127
6	0.5545	0.2803	0.9191	3.4708
8	0.6578	0.4399	0.4920	1.6444
10	0.6704	0.4492	0.5112	1.2879
b) Log T=4.8				
0	2.9690	3.8911	6.6326	9.5596
2	1.0256	1.8890	4.6325	7.5591
4	0.3679	0.3616	2.6346	5.5536
6	0.5495	0.2937	0.9004	3.4797
8	0.6148	0.3963	0.5884	1.7663
10	0.6203	0.4004	0.5974	1.5260
c) Log T=4.3				
0	2.8020	3.7789	6.8415	10.2365
2	0.8842	1.7707	4.8410	8.2352
4	0.3867	0.3445	2.8412	6.2244
6	0.5083	0.2808	1.1845	4.0926
8	0.5290	0.3132	0.9370	2.5096
10	0.5298	0.3140	0.9364	2.3516
d) Log T=3.7				
0	2.6830	3.7143	8.5567	14.0731
2	0.7898	1.6966	6.5538	12.0692
4	0.3913	0.3475	4.5411	10.0412
6	0.4651	0.2690	2.9544	7.8626
8	0.4664	0.2685	2.7510	6.4063
10	0.4664	0.2685	2.7485	6.2945

[a] The density $n=n_{\mathrm{H}}+n_{\mathrm{He}}$.

TABLE 3F

ION Ne III; CONFIGURATION $2p^4$

Density(cm^{-3})[a] Log(n)	RELATIVE POPULATIONS – Log(N_j)			
	N_2	N_3	N_4	N_5
a) Log T=5.3				
0...........	6.2469	6.3497	7.9401	10.3008
2...........	4.2470	4.3500	5.9401	8.3008
4...........	2.2577	2.3802	3.9402	6.3007
6...........	0.7165	1.2073	1.9551	4.2935
8...........	0.6038	1.1260	0.6071	2.2245
10...........	0.6618	1.1418	0.5214	1.3420
b) Log T=4.8				
0...........	6.0383	6.1075	7.8750	10.4286
2...........	4.0385	4.1080	5.8750	8.4286
4...........	2.0555	2.1551	3.8751	6.4283
6...........	0.6491	1.1349	1.8968	4.4126
8...........	0.5807	1.0805	0.6968	2.3378
10...........	0.6074	1.0878	0.6355	1.6459
c) Log T=4.3				
0...........	5.8579	5.8840	8.1942	11.3730
2...........	3.8582	3.8848	6.1942	9.3730
4...........	1.8832	1.9526	4.1940	7.3721
6...........	0.5979	1.0568	2.2201	5.3366
8...........	0.5223	1.0107	1.1394	3.2535
10...........	0.5252	1.0110	1.0895	2.7301
d) Log T=3.7				
0...........	5.7601	5.7890	10.4211	16.3783
2...........	3.7604	3.7900	8.4210	14.3782
4...........	1.7923	1.8805	6.4184	12.3747
6...........	0.5959	1.0729	4.4348	10.3019
8...........	0.5209	1.0322	3.4656	8.2542
10...........	0.5201	1.0318	3.4283	7.8480

[a] The density $n=n_{\mathrm{H}}+n_{\mathrm{He}}$.

TABLE 3G

ION Ne IV; CONFIGURATION $2p^3$

Density(cm^{-3})[a] Log(n)	RELATIVE POPULATIONS – Log(N_j)			
	N_2	N_3	N_4	N_5
a) Log T=5.6				
0...........	5.4381	6.5370	9.3978	9.4189
2...........	3.4386	4.5370	7.3977	7.4188
4...........	1.4879	2.5355	5.3919	5.4089
6...........	0.5318	0.8453	3.3108	3.3209
8...........	0.4888	0.6268	1.4918	1.3916
10...........	0.5256	0.7001	1.0467	0.7509
b) Log T=5.1				
0...........	5.3338	6.4401	9.3592	9.3803
2...........	3.3347	4.4400	7.3590	7.3800
4...........	1.4087	2.4313	5.3426	5.3571
6...........	0.5765	0.8302	3.1978	3.2099
8...........	0.5333	0.6815	1.4704	1.3241
10...........	0.5459	0.7214	1.1343	0.8362
c) Log T=4.6				
0...........	5.5416	6.6661	9.7795	9.8007
2...........	3.5427	4.6656	7.7790	7.8000
4...........	1.6365	2.6340	5.7346	5.7459
6...........	0.8131	1.0425	3.4453	3.4563
8...........	0.7283	0.8913	1.7910	1.6001
10...........	0.7059	0.8824	1.5185	1.2192
d) Log T=4.0				
0...........	7.2130	8.3660	12.4194	12.4409
2...........	5.2144	6.3649	10.4182	10.4395
4...........	3.3339	4.2987	8.3306	8.3375
6...........	2.4890	2.7173	5.8847	5.8907
8...........	2.3999	2.5781	4.3697	4.1391
10...........	2.3932	2.5721	4.1920	3.8923

[a] The density $n=n_{\mathrm{H}}+n_{\mathrm{He}}$.

TABLE 3H

ION Ne V; CONFIGURATION $2p^2$

Density (cm^{-3})[a] Log(n)	RELATIVE POPULATIONS – Log(N_j)			
	N_2	N_3	N_4	N_5
a) Log T=5.7				
0...........	5.2809	6.1883	8.4319	10.4197
2...........	3.2812	4.1883	6.4319	8.4197
4...........	1.3094	2.1870	4.4318	6.4193
6...........	0.3214	0.4707	2.4350	4.4142
8...........	0.5532	0.3324	0.7562	2.4006
10...........	0.6728	0.4572	0.4985	1.2888
b) Log T=5.5				
0...........	5.1884	6.0993	8.3549	10.3660
2...........	3.1888	4.0993	6.3549	8.3660
4...........	1.2235	2.0975	4.3548	6.3655
6...........	0.3329	0.4337	2.3586	4.3597
8...........	0.5593	0.3405	0.7296	2.3456
10...........	0.6655	0.4490	0.5106	1.3157
c) Log(T)=5.3				
0...........	5.1002	6.0166	8.2917	10.3397
2...........	3.1006	4.0165	6.2917	8.3397
4...........	1.1430	2.0141	4.2915	6.3391
6...........	0.3460	0.4036	2.2959	4.3322
8...........	0.5627	0.3453	0.7180	2.3167
10...........	0.6531	0.4362	0.5307	1.3667
d) Log T=5.1				
0...........	5.0175	5.9425	8.2498	10.3566
2...........	3.0180	3.9425	6.2498	8.3566
4...........	1.0690	1.9390	4.2496	6.3558
6...........	0.3593	0.3803	2.2543	4.3472
8...........	0.5617	0.3448	0.7270	2.3283
10...........	0.6339	0.4172	0.5645	1.4554

[a] The density $n=n_{\mathrm{H}}+n_{\mathrm{He}}$.

TABLE 3I

ION Mg V; CONFIGURATION $2p^4$

Density (cm^{-3})^a Log(n)	RELATIVE POPULATIONS −Log(N_j)			
	N_2	N_3	N_4	N_5
a) Log T=5.8				
0...........	7.9142	8.0231	9.3310	11.2391
2...........	5.9142	6.0231	7.3310	9.2391
4...........	3.9145	4.0239	5.3310	7.2391
6...........	1.9361	2.0924	3.3316	5.2390
8...........	0.6197	1.1790	1.3894	3.2307
10...........	0.6378	1.1493	0.5229	1.4997
b) Log T=5.3				
0...........	7.6924	7.7785	9.1593	11.1542
2...........	5.6924	5.7786	7.1593	9.1542
4...........	3.6928	3.7798	5.1594	7.1542
6...........	1.7281	1.8888	3.1602	5.1538
8...........	0.5887	1.1400	1.2514	3.1359
10...........	0.6307	1.1277	0.5573	1.5380
c) Log T=4.8				
0...........	7.5062	7.5471	9.1568	11.4273
2...........	5.5062	5.5471	7.1568	9.4273
4...........	3.5068	3.5491	5.1568	7.4273
6...........	1.5597	1.7072	3.1574	5.4257
8...........	0.5698	1.0861	1.2846	3.3816
10...........	0.5838	1.0728	0.7180	1.9203
d) Log T=4.3				
0...........	7.3511	7.3578	9.6822	12.8306
2...........	5.3511	5.3578	7.6822	10.8306
4...........	3.3520	3.3607	5.6822	8.8306
6...........	1.4242	1.5745	3.6800	6.8246
8...........	0.5489	1.0437	1.8392	4.7283
10...........	0.5258	1.0261	1.3767	3.4233

[a] The density $n=n_H+n_{He}$.

TABLE 3J

ION Mg VI; CONFIGURATION $2p^3$

Density (cm^{-3})^a Log(n)	RELATIVE POPULATIONS −Log(N_j)			
	N_2	N_3	N_4	N_5
a) Log T=5.9				
0...........	6.7466	8.1990	10.5734	10.6532
2...........	4.7467	6.1990	8.5734	8.6532
4...........	2.7494	4.1987	6.5732	6.6527
6...........	0.9608	2.1859	4.5585	4.6233
8...........	0.5188	0.7317	2.5045	2.5628
10...........	0.5155	0.6671	1.1448	0.9393
b) Log T=5.7				
0...........	6.6728	8.1270	10.5120	10.5917
2...........	4.6729	6.1270	8.5120	8.5917
4...........	2.6763	4.1266	6.5116	6.5910
6...........	0.9237	2.1101	4.4914	4.5543
8...........	0.5251	0.7209	2.4313	2.4879
10...........	0.5207	0.6762	1.1413	0.9204
c) Log T=5.5				
0...........	6.6141	8.0711	10.4728	10.5527
2...........	4.6141	6.0711	8.4728	8.5527
4...........	2.6182	4.0704	6.4723	6.5517
6...........	0.9032	2.0480	4.4437	4.5047
8...........	0.5375	0.7206	2.3738	2.4278
10...........	0.5283	0.6875	1.1513	0.9170
d) Log T=5.4				
0...........	6.5932	8.0521	10.4657	10.5456
2...........	4.5933	6.0521	8.4657	8.5456
4...........	2.5977	4.0513	6.4650	6.5444
6...........	0.9012	2.0247	4.4307	4.4908
8...........	0.5471	0.7255	2.3539	2.4062
10...........	0.5337	0.6947	1.1633	0.9231

[a] The density $n=n_H+n_{He}$.

TABLE 3K

ION Mg VII: CONFIGURATION $2p^2$

Density (cm^{-3})^a Log(n)	RELATIVE POPULATIONS −Log(N_j)			
	N_2	N_3	N_4	N_5
a) Log T=6.1				
0...........	6.9804	7.8379	9.7315	11.5702
2...........	4.9805	5.8379	7.7315	9.5702
4...........	2.9811	3.8379	5.7315	7.5702
6...........	1.0368	1.8370	3.7317	5.5691
8...........	0.3740	0.3650	1.7552	3.5586
10...........	0.6036	0.4198	0.5591	1.6677
b) Log T=6.0				
0...........	6.9321	7.7902	9.6867	11.5310
2...........	4.9322	5.7902	7.6867	9.5310
4...........	2.9328	3.7902	5.6867	7.5310
6...........	0.9948	1.7894	3.6868	5.5297
8...........	0.3816	0.3545	1.7129	3.5186
10...........	0.6070	0.4220	0.5551	1.6439
c) Log(T)=5.8				
0...........	6.8374	7.6973	9.6017	11.4620
2...........	4.8374	5.6973	7.6017	9.4620
4...........	2.8382	3.6973	5.6017	7.4620
6...........	0.9144	1.6965	3.6019	5.4603
8...........	0.3966	0.3371	1.6336	3.4476
10...........	0.6121	0.4240	0.5516	1.6082
d) Log T=5.6				
0...........	6.7457	7.6087	9.5259	11.4112
2...........	4.7458	5.6087	7.5259	9.4112
4...........	2.7468	3.6086	5.5259	7.4112
6...........	0.8396	1.6078	3.5260	5.4091
8...........	0.4109	0.3237	1.5641	3.3939
10...........	0.6141	0.4222	0.5555	1.5933

[a] The density $n=n_H+n_{He}$.

TABLE 3L

ION Si VII; CONFIGURATION $2p^4$

Density (cm^{-3})[a] Log(n)	RELATIVE POPULATIONS $-$Log(N_j) N_2	N_3	N_4	N_5
a) Log T=6.1				
0...........	9.2440	9.2683	10.4303	12.2439
2...........	7.2440	7.2683	8.4303	10.2439
4...........	5.2440	5.2683	6.4303	8.2439
6...........	3.2451	3.2729	4.4303	6.2439
8...........	1.3323	1.5689	2.4352	4.2432
10...........	0.5810	1.1423	0.7635	2.2436
b) Log T=6.0				
0...........	9.1964	9.2188	10.3861	12.2065
2...........	7.1964	7.2188	8.3861	10.2065
4...........	5.1964	5.2189	6.3861	8.2065
6...........	3.1977	3.2240	4.3862	6.2065
8...........	1.2931	1.5426	2.3915	4.2057
10...........	0.5819	1.1404	0.7453	2.2079
c) Log(T)=5.8				
0...........	9.1034	9.1207	10.3031	12.1427
2...........	7.1034	7.1207	8.3031	10.1427
4...........	5.1035	5.1208	6.3031	8.1427
6...........	3.1051	3.1272	4.3032	6.1426
8...........	1.2187	1.4930	2.3097	4.1414
10...........	0.5842	1.1358	0.7166	2.1477
d) Log T=5.6				
0...........	9.0144	9.0242	10.2303	12.1001
2...........	7.0144	7.0242	8.2303	10.1001
4...........	5.0145	5.0243	6.2303	8.1001
6...........	3.0165	3.0322	4.2304	6.1001
8...........	1.1507	1.4471	2.2381	4.0981
10...........	0.5865	1.1296	0.6998	2.1087

[a] The density $n=n_{\mathrm{H}}+n_{\mathrm{He}}$.

TABLE 3M

ION Si VIII; CONFIGURATION $2p^3$

Density (cm^{-3})[a] Log(n)	RELATIVE POPULATIONS $-$Log(N_j) N_2	N_3	N_4	N_5
a) Log T=6.2				
0...........	9.6486	8.0061	11.6441	11.7306
2...........	7.6486	6.0061	9.6441	9.7306
4...........	5.6486	4.0063	7.6441	7.7306
6...........	3.6471	2.0211	5.6427	5.7277
8...........	1.6488	0.6570	3.6087	3.6648
10...........	0.6556	0.5128	1.6666	1.6608
b) Log T=6.1				
0...........	9.6069	7.9639	11.6054	11.6919
2...........	7.6069	5.9639	9.6054	9.6919
4...........	5.6069	3.9641	7.6054	7.6919
6...........	3.6052	1.9806	5.6037	5.6885
8...........	1.6091	0.6506	3.5668	3.6225
10...........	0.6553	0.5146	1.6357	1.6229
c) Log T=6.0				
0...........	9.5666	7.9229	11.5687	11.6553
2...........	7.5666	5.9229	9.5687	9.6553
4...........	5.5665	3.9231	7.5687	7.6553
6...........	3.5645	1.9414	5.5668	5.6514
8...........	1.5706	0.6461	3.5265	3.5817
10...........	0.6562	0.5170	1.6069	1.5866
d) Log T=5.8				
0...........	9.4942	7.8488	11.5070	11.5938
2...........	7.4942	5.8488	9.5070	9.5938
4...........	5.4942	3.8490	7.5070	7.5938
6...........	3.4914	1.8714	5.5042	5.5887
8...........	1.5015	0.6439	3.4551	3.5095
10...........	0.6617	0.5239	1.5595	1.5229

[a] The density $n=n_{\mathrm{H}}+n_{\mathrm{He}}$.

TABLE 3N

ION Si IX; CONFIGURATION $2p^2$

Density (cm^{-3})[a] Log(n)	RELATIVE POPULATIONS $-$Log(N_j) N_2	N_3	N_4	N_5
a) Log T=6.3				
0...........	8.3487	9.1176	10.8065	12.5725
2...........	6.3487	7.1176	8.8065	10.5725
4...........	4.3487	5.1176	6.8065	8.5725
6...........	2.3513	3.1176	4.8065	6.5725
8...........	0.5650	1.1411	2.8073	4.5725
10...........	0.4795	0.3258	0.9768	2.5580
b) Log T=6.2				
0...........	8.3001	9.0695	10.7606	12.5311
2...........	6.3001	7.0695	8.7606	10.5311
4...........	4.3002	5.0695	6.7606	8.5311
6...........	2.3030	3.0695	4.7606	6.5311
8...........	0.5376	1.0971	2.7615	4.5309
10...........	0.4854	0.3278	0.9472	2.5154
c) Log T=6.1				
0...........	8.2528	9.0228	10.7165	12.4925
2...........	6.2528	7.0228	8.7165	10.4925
4...........	4.2528	5.0228	6.7165	8.4925
6...........	2.2560	3.0228	4.7165	6.4925
8...........	0.5126	1.0549	2.7175	4.4922
10...........	0.4911	0.3301	0.9201	2.4756
d) Log(T)=5.9				
0...........	8.1583	8.9301	10.6318	12.4236
2...........	6.1583	6.9301	8.6318	10.4236
4...........	4.1584	4.9301	6.6318	8.4236
6...........	2.1624	2.9301	4.6318	6.4236
8...........	0.4676	0.9731	2.6327	4.4228
10...........	0.5020	0.3353	0.8723	2.4039

[a] The density $n=n_{\mathrm{H}}+n_{\mathrm{He}}$.

TABLE 3O

Ion S II; Configuration $3p^3$

Density (cm^{-3})[a] Log(n)	RELATIVE POPULATIONS $-\text{Log}(N_j)$			
	N_2	N_3	N_4	N_5
	a) Log T=4.8			
0...........	5.2372	4.5268	8.2137	8.1466
2...........	3.2371	2.5321	6.2103	6.1422
4...........	1.2975	0.8651	4.0507	3.9627
6...........	0.6683	0.5472	1.9123	1.8208
8...........	0.7031	0.5336	1.1282	0.8421
10...........	0.7070	0.5327	1.1045	0.8043
	b) Log T=4.4			
0...........	5.2929	4.5713	8.3841	8.3177
2...........	3.2918	2.5779	6.3782	6.3102
4...........	1.3439	0.9496	4.1399	4.0522
6...........	0.7623	0.6304	1.9949	1.8876
8...........	0.7535	0.5847	1.3148	1.0246
10...........	0.7533	0.5819	1.2966	0.9974
	c) Log T=4.1			
0...........	5.5598	4.8251	8.8559	8.7907
2...........	3.5575	2.8318	6.8473	6.7800
4...........	1.5769	1.1943	4.5269	4.4392
6...........	0.9667	0.8239	2.3411	2.2204
8...........	0.9230	0.7587	1.7215	1.4307
10...........	0.9210	0.7554	1.7061	1.4086
	d) Log T=3.7			
0...........	6.6174	5.8675	10.5944	10.5326
2...........	4.6139	3.8734	8.5836	8.5194
4...........	2.5827	2.1929	6.1858	6.0990
6...........	1.8785	1.7338	3.9187	3.7910
8...........	1.8465	1.7007	3.3731	3.0868
10...........	1.8456	1.6996	3.3614	3.0697

[a] The density $n=n_{\text{H}}+n_{\text{He}}$.

TABLE 3P

Ion S III; Configuration $3p^2$

Density (cm^{-3})[a] Log(n)	RELATIVE POPULATIONS $-\text{Log}(N_j)$			
	N_2	N_3	N_4	N_5
	a) Log T=5.2			
0...........	3.9368	5.0317	6.8382	9.2200
2...........	1.9430	3.0306	4.8382	7.2200
4...........	0.3537	1.0355	2.8392	5.2183
6...........	0.5054	0.3020	0.9875	3.1633
8...........	0.6612	0.4502	0.4922	1.4671
10...........	0.6776	0.4580	0.4992	1.2632
	b) Log T=4.8			
0...........	3.7590	4.8668	6.7170	9.1828
2...........	1.7683	2.8650	4.7170	7.1827
4...........	0.3083	0.8890	2.7172	5.1788
6...........	0.5198	0.3097	0.9205	3.1001
8...........	0.6401	0.4283	0.5331	1.5353
10...........	0.6492	0.4328	0.5363	1.3934

TABLE 3P—*Continued*

Density (cm^{-3})[a] Log(n)	RELATIVE POPULATIONS $-\text{Log}(N_j)$			
	N_2	N_3	N_4	N_5
	c) Log T=4.3			
0...........	3.5704	4.7189	6.7386	9.5184
2...........	1.5850	2.7150	4.7384	7.5180
4...........	0.2863	0.7619	2.7332	5.5061
6...........	0.5087	0.3079	1.0028	3.3782
8...........	0.5714	0.3671	0.6975	1.9794
10...........	0.5738	0.3686	0.6957	1.8896
	d) Log T=3.8			
0...........	3.4786	4.7037	7.3503	11.1807
2...........	1.4970	2.6961	5.3492	9.1796
4...........	0.2849	0.7345	3.3238	7.1445
6...........	0.4558	0.2989	1.6190	4.9493
8...........	0.4724	0.3035	1.3430	3.6671
10...........	0.4726	0.3036	1.3392	3.6028

[a] The density $n=n_{\text{H}}+n_{\text{He}}$.

TABLE 3Q

Ion S IX; Configuration $2p^4$

Density (cm^{-3})[a] Log(n)	RELATIVE POPULATIONS $-\text{Log}(N_j)$			
	N_2	N_3	N_4	N_5
	a) Log T=6.3			
0...........	10.4019	10.2141	11.3632	13.1467
2...........	8.4019	8.2141	9.3632	11.1467
4...........	6.4019	6.2141	7.3632	9.1467
6...........	4.4020	4.2147	5.3632	7.1467
8...........	2.4119	2.2671	3.3638	5.1468
10...........	0.7852	1.2438	1.4185	3.1442
	b) Log T=6.2			
0...........	10.3539	10.1647	11.3177	13.1065
2...........	8.3539	8.1647	9.3177	11.1065
4...........	6.3539	6.1647	7.3177	9.1065
6...........	4.3540	4.1654	5.3177	7.1065
8...........	2.3650	2.2236	3.3184	5.1066
10...........	0.7653	1.2339	1.3789	3.1032
	c) Log T=6.0			
0...........	10.2606	10.0676	11.2315	13.0350
2...........	8.2606	8.0676	9.2315	11.0350
4...........	6.2606	6.0676	7.2315	9.0350
6...........	4.2608	4.0684	5.2315	7.0350
8...........	2.2743	2.1397	3.2323	5.0351
10...........	0.7308	1.2157	1.3057	3.0297
	d) Log T=5.9			
0...........	10.2150	10.0194	11.1910	13.0048
2...........	8.2150	8.0194	9.1910	11.0048
4...........	6.2150	6.0194	7.1910	9.0048
6...........	4.2152	4.0203	5.1910	7.0048
8...........	2.2301	2.0990	3.1919	5.0049
10...........	0.7159	1.2071	1.2725	2.9981

[a] The density $n=n_{\text{H}}+n_{\text{He}}$.

TABLE 3R

ION S X; CONFIGURATION $2p^3$

Density (cm^{-3})[a] Log(n)	RELATIVE POPULATIONS −Log(N_j)			
	N_2	N_3	N_4	N_5
a) Log T=6.3				
0	10.8219	9.1529	12.5122	12.5870
2	8.8219	7.1529	10.5122	10.5870
4	6.8219	5.1529	8.5122	8.5870
6	4.8219	3.1540	6.5121	6.5868
8	2.8177	1.2509	4.5014	4.5679
10	1.0101	0.5559	2.4518	2.4905
b) Log T=6.2				
0	10.7791	9.1096	12.4723	12.5473
2	8.7791	7.1096	10.4723	10.5473
4	6.7791	5.1097	8.4723	8.5473
6	4.7791	3.1109	6.4721	6.5470
8	2.7742	1.2176	4.4601	4.5259
10	0.9849	0.5561	2.4092	2.4471
c) Log T=6.1				
0	10.7390	9.0689	12.4357	12.5109
2	8.7390	7.0689	10.4357	10.5109
4	6.7390	5.0689	8.4357	8.5109
6	4.7389	3.0703	6.4355	6.5105
8	2.7331	1.1873	4.4218	4.4870
10	0.9624	0.5572	2.3693	2.4063
d) Log T=6.0				
0	10.7005	9.0298	12.4018	12.4772
2	8.7005	7.0298	10.4018	10.4772
4	6.7005	5.0298	8.4018	8.4772
6	4.7004	3.0313	6.4016	6.4769
8	2.6934	1.1594	4.3859	4.4505
10	0.9421	0.5595	2.3313	2.3673

[a] The density $n=n_{\mathrm{H}}+n_{\mathrm{He}}$.

TABLE 3S

ION S XI; CONFIGURATION $2p^2$

Density (cm^{-3})[a] Log(n)	RELATIVE POPULATIONS −Log(N_j)			
	N_2	N_3	N_4	N_5
a) Log T=6.3				
0	9.4663	10.1012	11.6300	13.3698
2	7.4663	8.1012	9.6300	11.3698
4	5.4663	6.1012	7.6300	9.3698
6	3.4665	4.1012	5.6300	7.3698
8	1.4868	2.1031	3.6302	5.3696
10	0.3736	0.4601	1.6591	3.3618
b) Log T=6.2				
0	9.4183	10.0539	11.5852	13.3304
2	7.4183	8.0539	9.5852	11.3304
4	5.4183	6.0539	7.5852	9.3304
6	3.4185	4.0539	5.5852	7.3304
8	1.4412	2.0560	3.5854	5.3302
10	0.3765	0.4436	1.6173	3.3210
c) Log T=6.1				
0	9.3717	10.0082	11.5426	13.2944
2	7.3717	8.0082	9.5426	11.2944
4	5.3717	6.0082	7.5426	9.2944
6	3.3719	4.0082	5.5426	7.2944
8	1.3972	2.0104	3.5428	5.2941
10	0.3800	0.4290	1.5777	3.2834
d) Log T=6.0				
0	9.3250	9.9626	11.5011	13.2613
2	7.3250	7.9626	9.5011	11.2613
4	5.3250	5.9626	7.5011	9.2613
6	3.3253	3.9626	5.5011	7.2613
8	1.3533	1.9651	3.5013	5.2609
10	0.3842	0.4156	1.5393	3.2483

[a] The density $n=n_{\mathrm{H}}+n_{\mathrm{He}}$.

TABLE 3T

ION Fe XI; CONFIGURATION $3p^4$

Density (cm^{-3})[a] Log(n)	RELATIVE POPULATIONS −Log(N_j)			
	N_2	N_3	N_4	N_5
a) Log T=6.3				
0	10.9450	9.4217	11.7812	13.6825
2	8.9450	7.4217	9.7812	11.6825
4	6.9450	5.4217	7.7812	9.6825
6	4.9454	3.4236	5.7812	7.6825
8	2.9744	1.5760	3.7814	5.6811
10	1.1546	1.0612	1.8164	3.5703
b) Log T=6.2				
0	10.8961	9.3727	11.7340	13.6389
2	8.8961	7.3727	9.7340	11.6389
4	6.8961	5.3727	7.7340	9.6389
6	4.8966	3.3747	5.7340	7.6388
8	2.9280	1.5424	3.7343	5.6372
10	1.1176	1.0607	1.7730	3.5158
c) Log T=6.1				
0	10.8484	9.3248	11.6885	13.5976
2	8.8484	7.3248	9.6885	11.5976
4	6.8484	5.3248	7.6885	9.5976
6	4.8489	3.3271	5.6885	7.5976
8	2.8829	1.5109	3.6887	5.5956
10	1.0825	1.0606	1.7314	3.4632
d) Log T=6.0				
0	10.8003	9.2764	11.6431	13.5577
2	8.8003	7.2764	9.6431	11.5577
4	6.8004	5.2765	7.6431	9.5577
6	4.8009	3.2790	5.6431	7.5577
8	2.8376	1.4805	3.6434	5.5555
10	1.0483	1.0608	1.6904	3.4110

[a] The density $n=n_{\mathrm{H}}+n_{\mathrm{He}}$.

TABLE 3U

Ion Fe xii; Configuration $3p^3$

Density (cm^{-3})[a] Log(n)	Relative Populations −Log(N_j) N_2	N_3	N_4	N_5
a) Log T=6.3				
0............	11.5049	10.2989	13.0211	13.1032
2............	9.5049	8.2989	11.0211	11.1032
4............	7.5049	6.2989	9.0211	9.1032
6............	5.5050	4.2990	7.0209	7.1028
8............	3.5062	2.3168	5.0017	5.0723
10............	1.5924	1.0015	2.6864	2.6821
b) Log T=6.2				
0............	11.4586	10.2525	12.9769	13.0595
2............	9.4586	8.2525	10.9769	11.0595
4............	7.4586	6.2525	8.9769	9.0595
6............	5.4587	4.2527	6.9767	7.0591
8............	3.4600	2.2725	4.9553	5.0251
10............	1.5543	0.9923	2.6320	2.6287
c) Log T=6.1				
0............	11.4141	10.2079	12.9350	13.0182
2............	9.4141	8.2079	10.9350	11.0182
4............	7.4141	6.2079	8.9350	9.0182
6............	5.4141	4.2081	6.9348	7.0178
8............	3.4156	2.2301	4.9109	4.9801
10............	1.5183	0.9841	2.5800	2.5778
d) Log T=6.0				
0............	11.3701	10.1638	12.8944	12.9784
2............	9.3701	8.1638	10.8944	10.9784
4............	7.3701	6.1638	8.8944	8.9784
6............	5.3701	4.1641	6.8941	6.9779
8............	3.3718	2.1884	4.8675	4.9360
10............	1.4834	0.9769	2.5290	2.5280

[a] The density $n=n_H+n_{He}$.

TABLE 3V

Ion Fe xiii; Configuration $3p^2$

Density (cm^{-3})[a] Log(n)	Relative Populations −Log(N_j) N_2	N_3	N_4	N_5
a) Log T=6.3				
0............	10.2237	10.3141	12.0987	13.9171
2............	8.2237	8.3141	10.0987	11.9171
4............	6.2237	6.3141	8.0987	9.9171
6............	4.2237	4.3141	6.0987	7.9171
8............	2.2289	2.3175	4.0989	5.9161
10............	0.5984	0.5814	2.1165	3.8336
b) Log T=6.2				
0............	10.1752	10.2657	12.0524	13.8735
2............	8.1752	8.2657	10.0524	11.8735
4............	6.1752	6.2657	8.0524	9.8735
6............	4.1752	4.2658	6.0524	7.8735
8............	2.1810	2.2696	4.0526	5.8724
10............	0.5811	0.5569	2.0717	3.7816
c) Log T=6.1				
0............	10.1279	10.2186	12.0079	13.8324
2............	8.1279	8.2186	10.0079	11.8324
4............	6.1279	6.2186	8.0079	9.8324
6............	4.1279	4.2187	6.0079	7.8324
8............	2.1344	2.2229	4.0081	5.8311
10............	0.5658	0.5346	2.0287	3.7315
d) Log T=6.0				
0............	10.0803	10.1714	11.9639	13.7928
2............	8.0803	8.1714	9.9639	11.7928
4............	6.0803	6.1714	7.9639	9.7928
6............	4.0804	4.1714	5.9639	7.7928
8............	2.0876	2.1761	3.9641	5.7913
10............	0.5518	0.5137	1.9861	3.6819

[a] The density $n=n_H+n_{He}$.

Notes to Tables 3A–3V.

The relative populations (N_j) are given for different temperatures and densities. In Tables 3A–3V (the q=2,3,4 ions) N_2, N_3, N_4, and N_5 are given. The temperature range was chosen so that the relevant ionic abundances in the time-dependent cooling case (see text) were above ~5%. These temperature ranges should be adequate for most purposes. Extrapolations to temperatures outside the given range can be carried out if desired. The results are presented as a function of the density n, rather than n_e, the density being a parameter which does not change even if the gas recombines. Below $T \approx 10^4$ K, the results are strictly correct for a gas that is cooling radiatively, although the results should roughly be applicable to cases where there is no time variation of n_e (like H II regions). The values of N_1 can be found from the requirement that all N_j when summed are equal to 1.

of the excitation rates is simply a ratio of the collision strengths. If the radiative transition probabilities or the collisional de-excitation rates are different, then the ratio of the relative populations of these two levels will depend on the density, and thus the ratio of the line intensities depends on the density (see also Osterbrock 1974).

On the other hand, for ions with q=2,4, the line ratio

$$\sum_{J=0}^{2} I(^1D_2-^3P_J)/I(^1S_0-^1D_2)$$

shows temperature dependence for the following reason: The energy difference between the $^1S_0$ and $^1D_2$ levels is

TABLE 4A

ION C II; CONFIGURATION 2*p*

Log(n)[a] (cm^{-3})	Relative Population −Log(N_2)
a) Log T=4.8	
0...........	1.9718
2...........	0.3843
4...........	0.1790
6...........	0.1763
8...........	0.1763
10...........	0.1763
b) Log T=4.4	
0...........	1.7804
2...........	0.3201
4...........	0.1783
6...........	0.1766
8...........	0.1766
10...........	0.1766
c) Log T=4.1	
0...........	1.6510
2...........	0.2870
4...........	0.1784
6...........	0.1772
8...........	0.1772
10...........	0.1772
d) Log T=3.7	
0...........	1.5665
2...........	0.2701
4...........	0.1798
6...........	0.1788
8...........	0.1788
10...........	0.1788

[a] The density $n=n_{\mathrm{H}}+n_{\mathrm{He}}$ (n is the total number density of hydrogen and helium nuclei).

TABLE 4B

ION N III; CONFIGURATION 2*p*

Log(n)[a] (cm^{-3})	Relative Population −Log(N_2)
a) Log T=5.1	
0...........	3.5308
2...........	1.5494
4...........	0.2649
6...........	0.1774
8...........	0.1764
10...........	0.1764
b) Log T=4.6	
0...........	3.2856
2...........	1.3178
4...........	0.2294
6...........	0.1776
8...........	0.1770
10...........	0.1770

TABLE 4B—*Continued*

Log(n)[a] (cm^{-3})	Relative Population −Log(N_2)
c) Log T=4.1	
0...........	3.0590
2...........	1.1122
4...........	0.2107
6...........	0.1793
8...........	0.1790
10...........	0.1790
d) Log T=3.7	
0...........	2.9795
2...........	1.0433
4...........	0.2097
6...........	0.1837
8...........	0.1834
10...........	0.1834

TABLE 4C

ION O IV; CONFIGURATION 2*p*

Log(n)[a] (cm^{-3})	Relative Population −Log(N_2)
a) Log T=5.4	
0...........	4.8470
2...........	2.8480
4...........	0.9311
6...........	0.1963
8...........	0.1766
10...........	0.1764
b) Log T=4.9	
0...........	4.5998
2...........	2.6014
4...........	0.7390
6...........	0.1884
8...........	0.1772
10...........	0.1771
c) Log T=4.4	
0...........	4.3608
2...........	2.3636
4...........	0.5805
6...........	0.1859
8...........	0.1794
10...........	0.1793
d) Log T=4.0	
0...........	4.2040
2...........	2.2080
4...........	0.4952
6...........	0.1888
8...........	0.1843
10...........	0.1842

TABLE 4D

ION Ne II; CONFIGURATION $2p^5$

Log(n)[a] (cm^{-3})	Relative Population −Log(N_2)
a) Log T=5.0	
0...........	6.6918
2...........	4.6918
4...........	2.6945
6...........	0.8998
8...........	0.4874
10...........	0.4804
b) Log T=4.6	
0...........	6.5018
2...........	4.5019
4...........	2.5060
6...........	0.7947
8...........	0.4898
10...........	0.4853
c) Log T=4.2	
0...........	6.3297
2...........	4.3298
4...........	2.3360
6...........	0.7229
8...........	0.5008
10...........	0.4979
d) Log T=3.7	
0...........	6.2612
2...........	4.2613
4...........	2.2695
6...........	0.7264
8...........	0.5464
10...........	0.5442

TABLE 4E

ION Ne VI; CONFIGURATION $2p$

Log(n)[a] (cm^{-3})	Relative Population −Log(N_2)
a) Log T=5.8	
0...........	6.9085
2...........	4.9085
4...........	2.9094
6...........	0.9824
8...........	0.1993
10...........	0.1768
b) Log T=5.7	
0...........	6.8591
2...........	4.8591
4...........	2.8600
6...........	0.9411
8...........	0.1971
10...........	0.1768
c) Log T=5.5	
0...........	6.7598
2...........	4.7598
4...........	2.7610
6...........	0.8606
8...........	0.1933
10...........	0.1771
d) Log T=5.4	
0...........	6.7107
2...........	4.7107
4...........	2.7120
6...........	0.8222
8...........	0.1918
10...........	0.1773

TABLE 4F

ION Mg IV; CONFIGURATION $2p^5$

Log(n)[a] (cm^{-3})	Relative Population −Log(N_2)
a) Log T=5.6	
0...........	8.2671
2...........	6.2671
4...........	4.2671
6...........	2.2741
8...........	0.6871
10...........	0.4821
b) Log T=5.0	
0...........	7.9776
2...........	5.9776
4...........	3.9777
6...........	1.9914
8...........	0.6037
10...........	0.4878
c) Log T=4.4	
0...........	7.7239
2...........	5.7239
4...........	3.7241
6...........	1.7499
8...........	0.5799
10...........	0.5154
d) Log T=3.8	
0...........	7.6693
2...........	5.6693
4...........	3.6696
6...........	1.7077
8...........	0.6799
10...........	0.6357

TABLE 4G

ION Mg VIII; CONFIGURATION $2p$

$\mathrm{Log}(n)^{a}(\mathrm{cm}^{-3})$	Relative Population $-\mathrm{Log}(N_2)$
a) Log $T=6.2$	
0	8.6488
2	6.6488
4	4.6489
6	2.6503
8	0.7750
10	0.1892
b) Log $T=6.1$	
0	8.5998
2	6.5998
4	4.5998
6	2.6015
8	0.7389
10	0.1880
c) Log $T=5.9$	
0	8.5006
2	6.5006
4	4.5007
6	2.5027
8	0.6693
10	0.1860
d) Log $T=5.8$	
0	8.4512
2	6.4512
4	4.4512
6	2.4535
8	0.6365
10	0.1853

TABLE 4H

ION Si II; CONFIGURATION $3p$

$\mathrm{Log}(n)^{a}(\mathrm{cm}^{-3})$	Relative Population $-\mathrm{Log}(N_2)$
a) Log $T=4.7$	
0	3.4393
2	1.4622
4	0.2502
6	0.1781
8	0.1773
10	0.1773
b) Log $T=4.4$	
0	3.2958
2	1.3275
4	0.2319
6	0.1791
8	0.1785
10	0.1785
c) Log $T=4.1$	
0	3.1681
2	1.2103
4	0.2211
6	0.1813
8	0.1809
10	0.1809
d) Log $T=3.7$	
0	3.0970
2	1.1471
4	0.2221
6	0.1887
8	0.1883
10	0.1883

TABLE 4I

ION Si VI; CONFIGURATION $2p^5$

$\mathrm{Log}(n)^{a}(\mathrm{cm}^{-3})$	Relative Population $-\mathrm{Log}(N_2)$
a) Log $T=6.0$	
0	9.6354
2	7.6354
4	5.6354
6	3.6357
8	1.6647
10	0.5374
b) Log $T=5.6$	
0	9.4404
2	7.4404
4	5.4404
6	3.4409
8	1.4858
10	0.5202
c) Log $T=5.2$	
0	9.2524
2	7.2524
4	5.2524
6	3.2531
8	1.3217
10	0.5150
d) Log $T=4.8$	
0	9.0841
2	7.0841
4	5.0841
6	3.0852
8	1.1870
10	0.5273

TABLE 4J

Ion Si x; Configuration $2p$

$\mathrm{Log}(n)^a$ (cm^{-3})	Relative Population $-\mathrm{Log}(N_2)$
a) Log T=6.3	
0	9.7471
2	7.7471
4	5.7471
6	3.7472
8	1.7587
10	0.3141
b) Log T=6.2	
0	9.6975
2	7.6975
4	5.6975
6	3.6976
8	1.7104
10	0.3013
c) Log T=6.1	
0	9.6488
2	7.6488
4	5.6488
6	3.6490
8	1.6632
10	0.2899
d) Log T=6.0	
0	9.5995
2	7.5995
4	5.5995
6	3.5997
8	1.6156
10	0.2794

TABLE 4K

Ion S iv; Configuration $3p$

$\mathrm{Log}(n)^a$ (cm^{-3})	Relative Population $-\mathrm{Log}(N_2)$
a) Log T=5.3	
0	5.6551
2	3.6553
4	1.6693
6	0.2912
8	0.1784
10	0.1771
b) Log T=5.2	
0	5.6060
2	3.6062
4	1.6219
6	0.2806
8	0.1785
10	0.1773

TABLE 4K—*Continued*

$\mathrm{Log}(n)^a$ (cm^{-3})	Relative Population $-\mathrm{Log}(N_2)$
c) Log T=5.0	
0	5.5084
2	3.5086
4	1.5283
6	0.2623
8	0.1790
10	0.1781
d) Log T=4.8	
0	5.4130
2	3.4133
4	1.4377
6	0.2479
8	0.1800
10	0.1792

TABLE 4L

Ion S viii; Configuration $2p^5$

$\mathrm{Log}(n)^a$ (cm^{-3})	Relative Population $-\mathrm{Log}(N_2)$
a) Log T=6.3	
0	10.8214
2	8.8214
4	6.8214
6	4.8214
8	2.8234
10	0.9842
b) Log T=6.1	
0	10.7236
2	8.7236
4	6.7236
6	4.7237
8	2.7261
10	0.9199
c) Log T=5.9	
0	10.6264
2	8.6264
4	6.6264
6	4.6265
8	2.6295
10	0.8614
d) Log T=5.7	
0	10.5312
2	8.5312
4	6.5312
6	4.5312
8	2.5350
10	0.8099

TABLE 4M

ION S XII; CONFIGURATION $2p$

$\mathrm{Log}(n)^{\mathrm{a}}(\mathrm{cm}^{-3})$	Relative Population $-\mathrm{Log}(N_2)$
a) Log $T=6.3$	
0	10.7426
2	8.7426
4	6.7426
6	4.7426
8	2.7438
10	0.8472
b) Log $T=6.2$	
0	10.6935
2	8.6935
4	6.6935
6	4.6935
8	2.6948
10	0.8091
c) Log $T=6.1$	
0	10.6454
2	8.6454
4	6.6454
6	4.6455
8	2.6469
10	0.7729
d) Log $T=6.0$	
0	10.5970
2	8.5970
4	6.5970
6	4.5970
8	2.5986
10	0.7374

TABLE 4N

ION Fe X; CONFIGURATION $3p^5$

$\mathrm{Log}(n)^{\mathrm{a}}(\mathrm{cm}^{-3})$	Relative Population $-\mathrm{Log}(N_2)$
a) Log $T=6.3$	
0	11.1776
2	9.1776
4	7.1776
6	5.1776
8	3.1785
10	1.2571
b) Log $T=6.2$	
0	11.1286
2	9.1286
4	7.1286
6	5.1287
8	3.1296
10	1.2169

TABLE 4N—*Continued*

$\mathrm{Log}(n)^{\mathrm{a}}(\mathrm{cm}^{-3})$	Relative Population $-\mathrm{Log}(N_2)$
c) Log $T=6.0$	
0	11.0327
2	9.0327
4	7.0327
6	5.0327
8	3.0339
10	1.1407
d) Log $T=5.8$	
0	10.9383
2	8.9383
4	6.9383
6	4.9384
8	2.9399
10	1.0700

TABLE 4O

ION Fe XIV; CONFIGURATION $3p$

$\mathrm{Log}(n)^{\mathrm{a}}(\mathrm{cm}^{-3})$	Relative Population $-\mathrm{Log}(N_2)$
a) Log $T=6.3$	
0	10.9827
2	8.9827
4	6.9827
6	4.9827
8	2.9833
10	1.0459
b) Log $T=6.2$	
0	10.9340
2	8.9340
4	6.9340
6	4.9340
8	2.9347
10	1.0042
c) Log $T=6.1$	
0	10.8865
2	8.8865
4	6.8865
6	4.8865
8	2.8874
10	0.9643
d) Log $T=6.0$	
0	10.8388
2	8.8388
4	6.8388
6	4.8388
8	2.8397
10	0.9249

NOTES TO TABLES 4A–4O

The relative populations (N_j) are given for different temperatures and densities. In Tables 4A–4O (the $q=1,5$ ions) N_2 is given. The temperature range was chosen so that the relevant ionic abundances in the time-dependent cooling case (see text) were above ~5%. These temperature ranges should be adequate for most purposes. Extrapolations to temperatures outside the given range can be carried out if desired. The results are presented as a function of the density n, rather than n_e, the density being a parameter which does not change even if the gas recombines. Below $T \approx 10^4$ K, the results are strictly correct for a gas that is cooling radiatively, although the results should roughly be applicable to cases where there is no time variation of n_e (like H II regions). The values of N_1 can be found from the requirement that all N_j when summed are equal to 1.

large enough so that the relative populations will depend on temperature, as will the ratio of the line intensities arising from these two levels. We note here that the intensity of transition ${}^1D_2-{}^3P_0$ is comparatively weaker than the other two transitions between the ${}^1D$ and ${}^3P$ levels, and it is neglected in the above sum.

In Figures 8*a*–8*n* we show the ratio of the line strengths

$$\left[I({}^1D_2-{}^3P_1)+I({}^1D_2-{}^3P_2)\right]/I({}^1S_0-{}^1D_2)$$

for the $q=2,4$ ions: N II, Figure 8*a*; O I, 8*b*; O III, 8*c*; Ne III, 8*d*; Ne V, 8*e*; Mg V, 8*f*; Mg VII, 8*g*; Si VII, 8*h*; Si IX, 8*i*; S III, 8*j*; S IX, 8*k*; S XI, 8*l*; Fe XI, 8*m*; Fe XIII, 8*n*. This ratio is given as a function of temperature for different

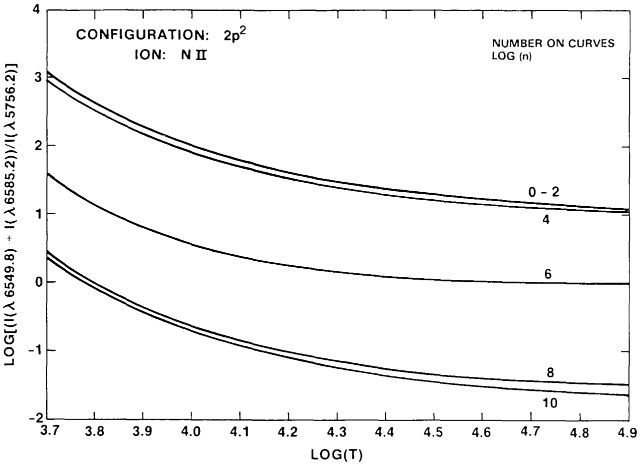

FIG. 8*a*

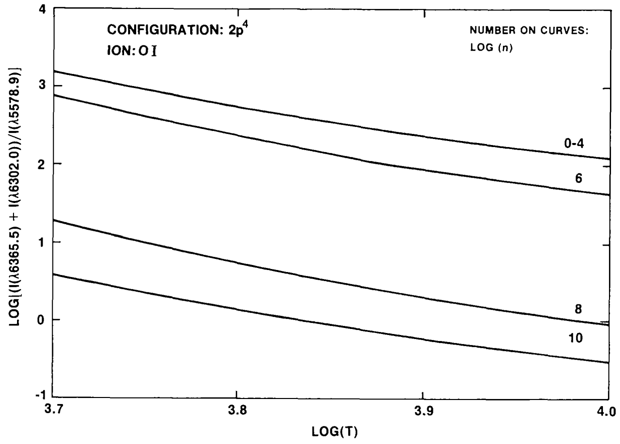

FIG. 8*b*

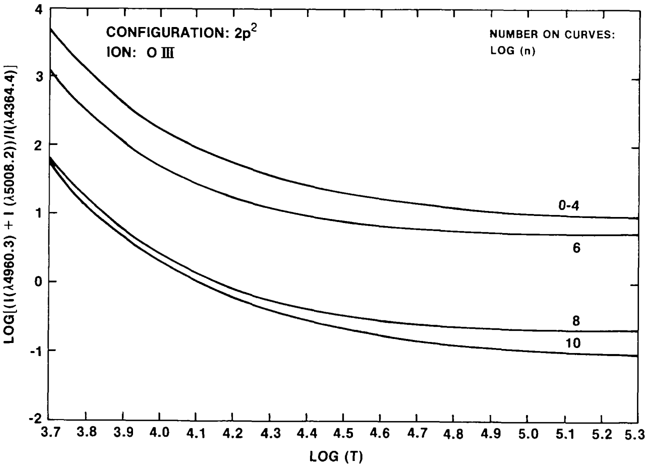

FIG. 8*c*

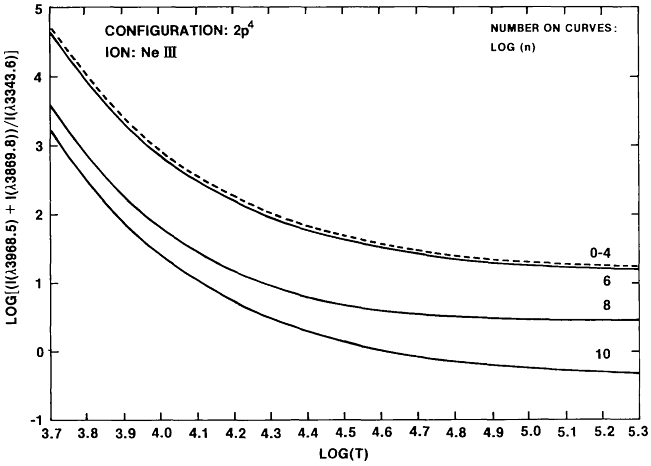

FIG. 8*d*

FIGS. 8*a*–8*n*.—The ratio $[I({}^1D_2-{}^3P_1)+I({}^1D_2-{}^3P_2)]/I({}^1S_0-{}^1D_2)$ as a function of temperature for the $q=2,4$ ions. Curves labeled according to the total density n.

1980ApJS...42..611K

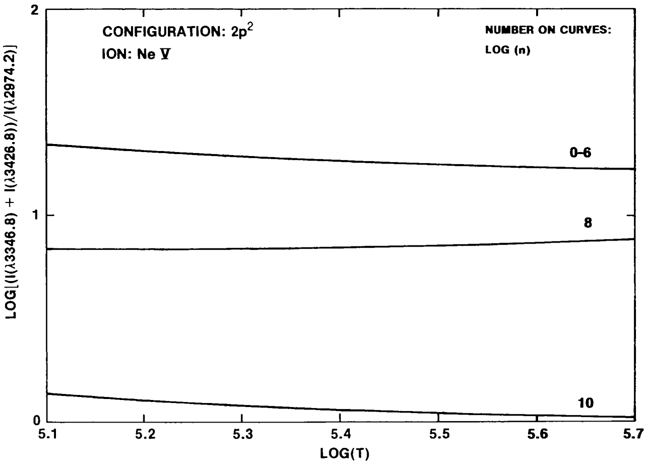

FIG. 8*e*

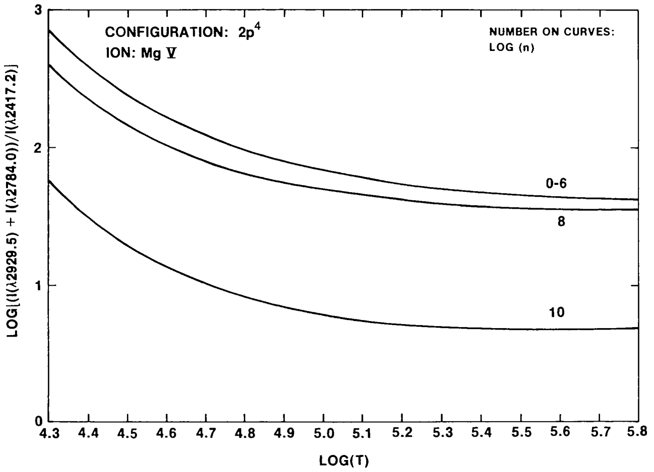

FIG. 8*f*

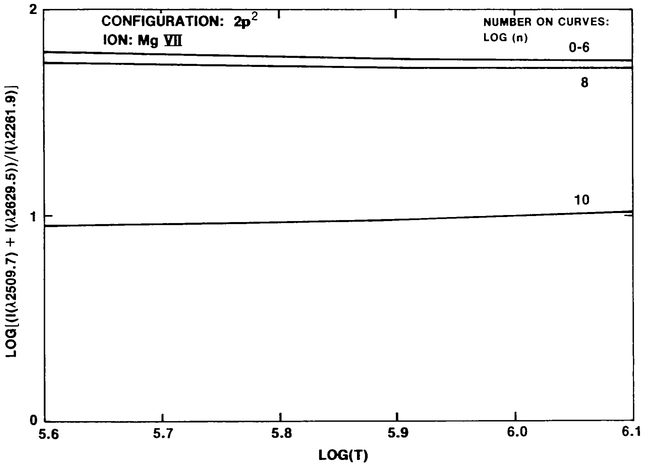

FIG. 8*g*

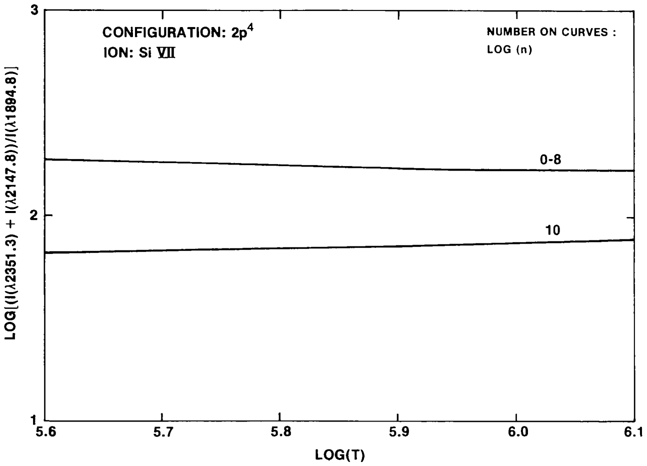

FIG. 8*h*

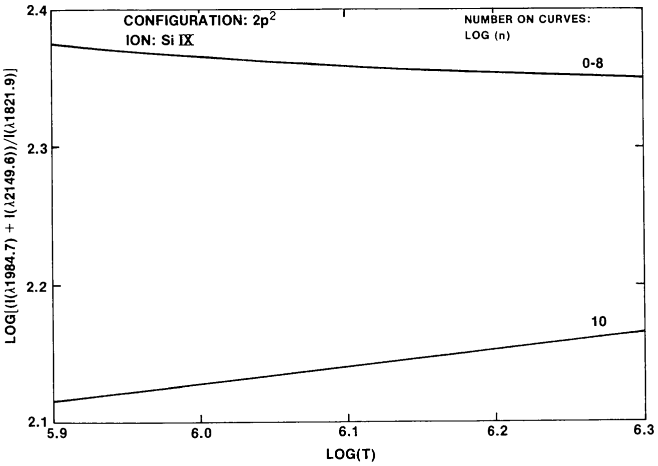

FIG. 8*i*

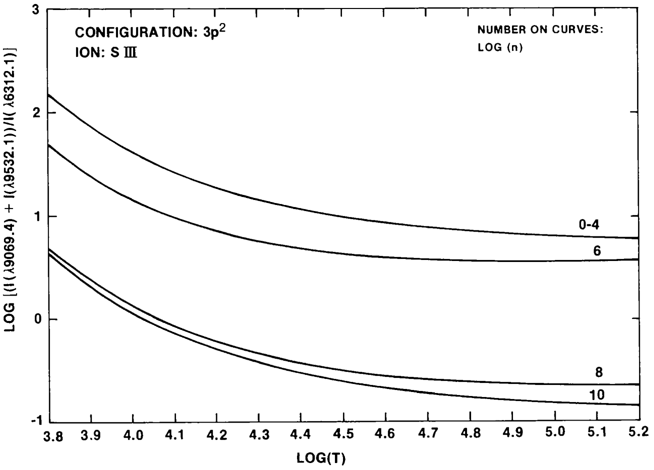

FIG. 8*j*

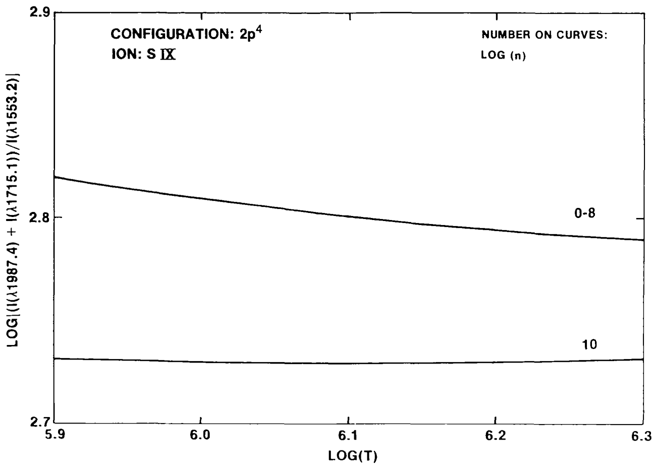

FIG. 8k

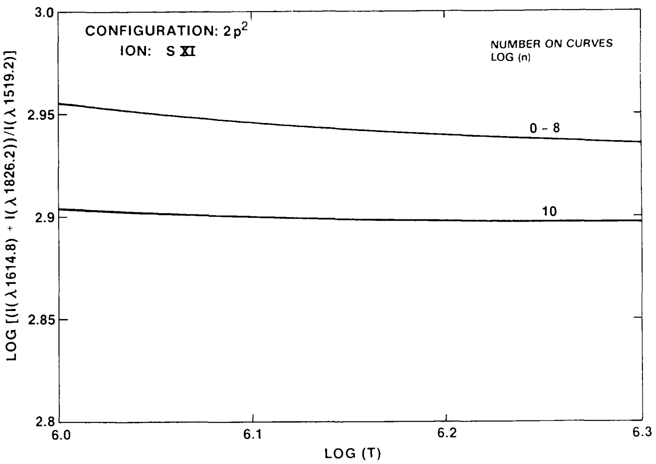

FIG. 8l

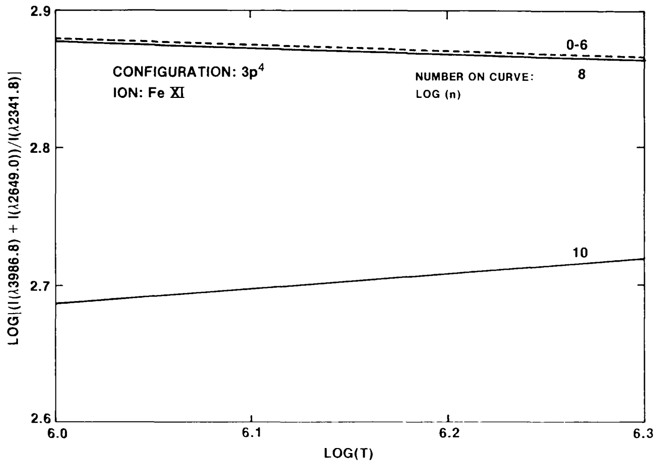

FIG. 8m

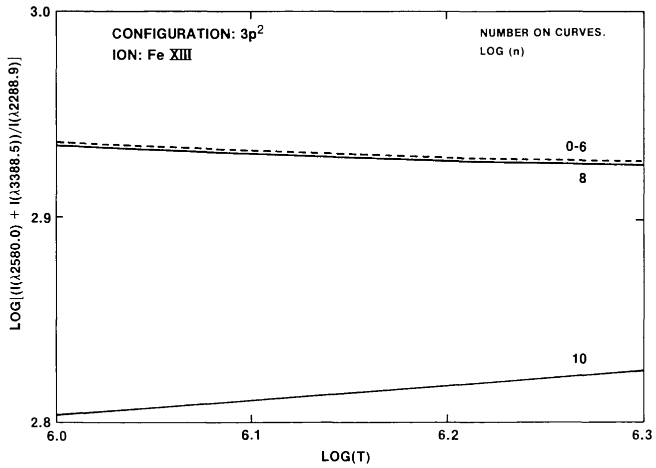

FIG. 8n

densities n. If there is little difference between curves for different densities, the range of the densities is given for a single curve.

For completeness we have plotted all the ratios, even though for some ions (e.g., Ne V, Mg VII, etc.) there is little variation of the ratio for different temperatures. We, in fact, note that for any ion at any density, the ratio eventually varies little for high enough temperatures. For high densities, this can be shown easily: the ratio of the factors b_3/b_2 which express deviations of the N_j's from thermodynamic equilibrium (Aller and Liller 1968) approaches 1 at high densities. Equation (2) then yields a line ratio proportional to $\exp(-E_{D,P}/kT)\exp(E_{S,P}/kT)$, where $E_{D,P}$ and $E_{S,P}$ is the energy difference between the ${}^1D$ and ${}^3P$ multiplet, and between the ${}^1S$ and ${}^3P$ multiplet, respectively. We see that at sufficiently high temperatures, $kT \gg E_{D,P}$, $E_{S,P}$, and therefore there is little temperature dependence for the line ratio. Similar considerations hold for other densities, although the proof is more complicated. We point out that if, of course, we had plotted the line ratio for these $q=2,4$ ions at lower temperatures, there would be strong temperature dependence; this, however, wouldn't be of any use since at lower temperatures, the abundance of the ion under consideration is less than ~1%. We have also examined other line ratios for these ions (Ne V, Mg VII, etc.) with similarly little dependence.

In Figure 9a–9h we show the ratio of the line strengths $I({}^2D_{5/2}-{}^4S_{3/2})/I({}^2D_{3/2}-{}^4S_{3/2})$ for the $q=3$ ions: N I, Figure 9a; O II, 9b; Ne IV, 9c; Mg VI, 9d; Si VIII, 9e; S II, 9f; S X, 9g; Fe XII, 9h. The ratio is given as a function of the density n for the two limits of the temperature ranges of Tables 3A, 3D, 3G, 3J, 3M, 3O, 3R, and 3U. It is obvious that there is little temperature dependence. At sufficiently low as well as at sufficiently high densities this line ratio becomes constant (see also Osterbrock 1974); at intermediate densities, however, the ratio shows strong density dependence.

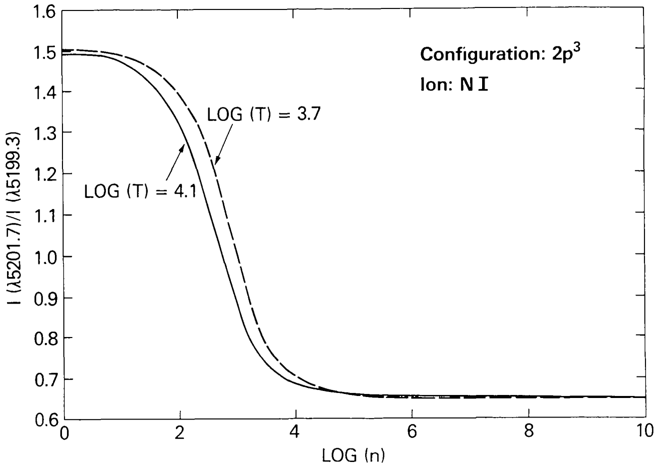

FIG. 9*a*

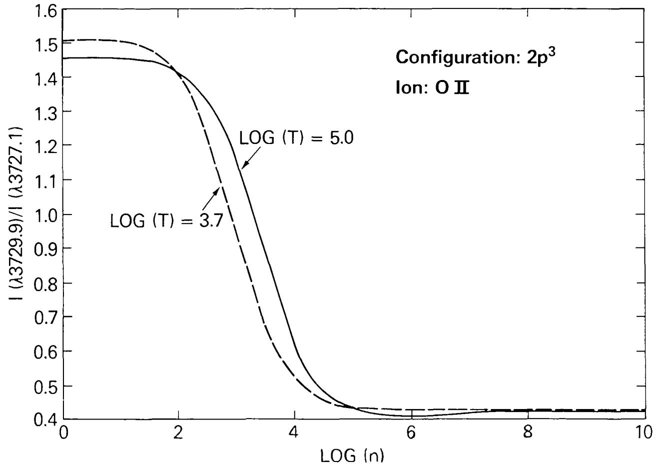

FIG. 9*b*

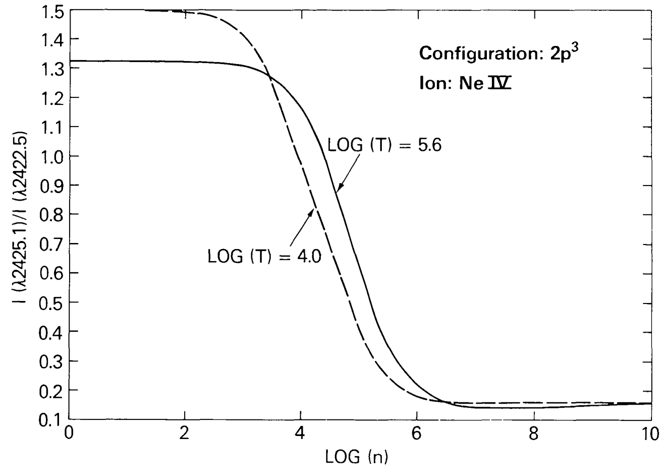

FIG. 9*c*

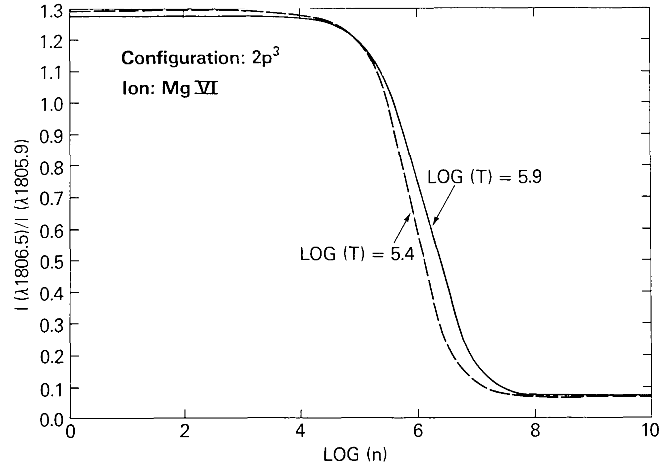

FIG. 9*d*

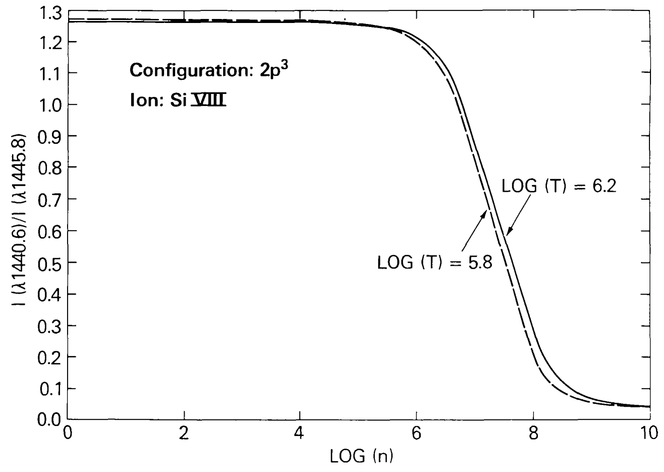

FIG. 9*e*

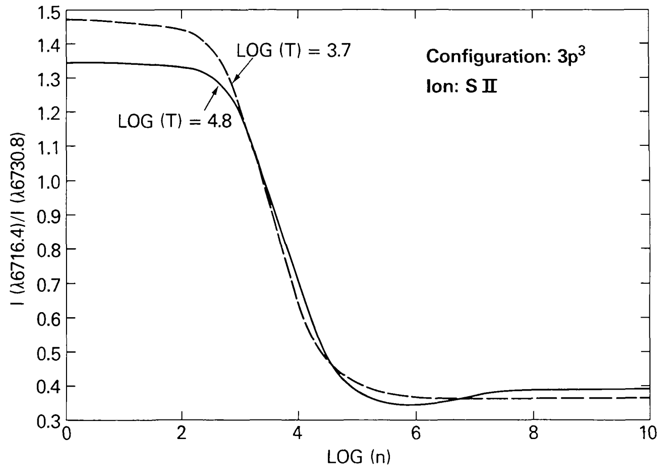

FIG. 9*f*

FIGS. 9*a*–9*h*.—The ratio $I(^2D_{5/2}-{}^4S_{3/2})/I(^2D_{3/2}-{}^4S_{3/2})$ as a function of density for the two limits of the temperature ranges of Tables 3A, 3D, 3G, 3J, 3M, 3O, 3R, and 3U, respectively. The ions have $q=3$.

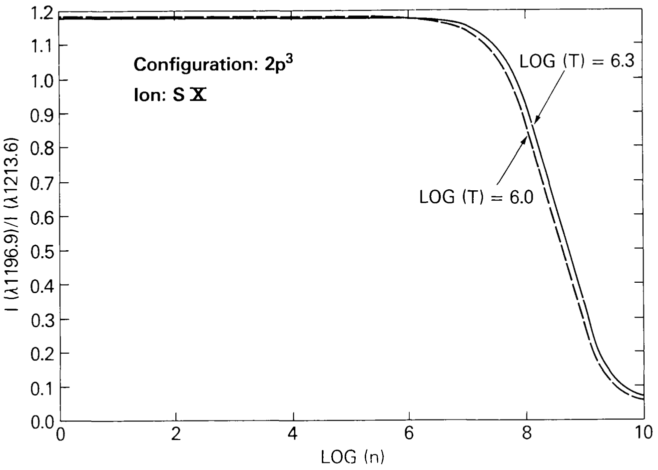

FIG. 9*g*

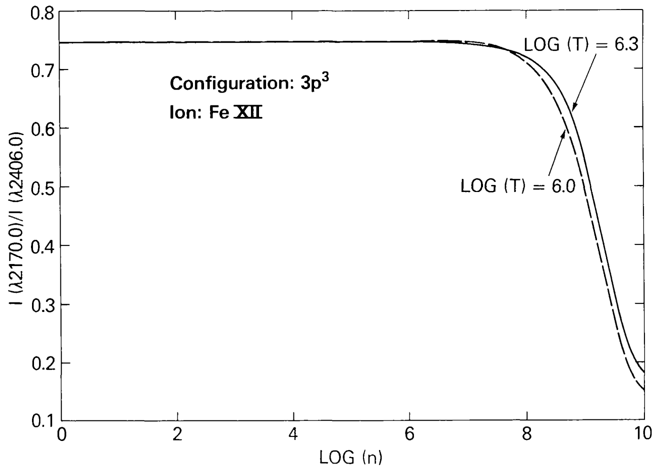

FIG. 9*h*

We compared our results to those published in other works (e.g., Osterbrock 1974) and we found satisfactory agreement in all cases. Whenever small differences existed, they could be explained by the small differences in the atomic data used.

It is hoped that the results presented here will be useful to researchers in the UV, visible, and IR fields. If different line ratios are desired, they can be easily obtained from the tabulated atomic data and the tabulated N_j's, by using equation (2). If absolute intensities are required, equation (1) can be used, although the reader will have to provide the required $N_{A,Z}$ values. Our computations can be used for diagnostic purposes to determine temperatures and densities of hot plasmas in the temperature range 5×10^3–2×10^6 K. Even though radiative cooling is very strong in this range, little information exists (with the exception of the *Copernicus* observations) above 10^5 K, although the O VI observations indicate that a sizable portion of the interstellar medium is in the very hot state. In a future work, we plan to present absolute line intensity calculations in important cases.

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APPENDIX

FORMULAE FOR THE CALCULATIONS OF THE RELATIVE POPULATIONS IN A FIVE LEVEL GROUND STATE TERM

We present here the solutions of the detailed balance equations in a five level ground state term. The results are, of course, applicable to other five level systems besides the $q=2,3,4$ ions presented in the present work. In giving the solutions we have avoided the detailed derivation of the results and have given instead the final formulae.

The equilibrium equations for the five levels (see also Osterbrock 1974) are of the form

$$\sum_{j\neq i} N_j n_e q_{ji} + \sum_{j>i} N_j A_{ji} = \sum_{j\neq i} N_i n_e q_{ij} + \sum_{j<i} N_i A_{ij}, \tag{A1}$$

where the collisional excitation rate per unit volume, q_{ij}, and the collisional de-excitation rate per unit volume, q_{ji}, are given by $(i<j)$:

$$q_{ij} = q_{ji} e^{-E_{ij}/kT} \frac{\omega_j}{\omega_i},$$

$$q_{ji} = \frac{8.629\times10^{-6}\Omega_{ij}}{\sqrt{T}\,\omega_j}. \tag{A2}$$

In (A2), ω_i and ω_j are the statistical weights of the i and j levels, respectively, and Ω_{ij} is the collision strength (symmetrical in the i and j indices). We set $i=2,3,4,5$ in the system of equations (A1); the fifth equation of the system is

$$N_1+N_2+N_3+N_4+N_5=1. \tag{A3}$$

Defining the following parameters (E_{ij} is the energy difference between levels i and j, n_e in the electron density),

$$A_2=\frac{C}{\omega_2}\left\{\Omega_{12}+\Omega_{23}e^{-E_{23}/kT}+\Omega_{24}e^{-E_{24}/kT}+\Omega_{25}e^{-E_{25}/kT}\right\}+A_{21}$$

$$A_3=\frac{C}{\omega_3}\left\{\Omega_{13}+\Omega_{23}+\Omega_{34}e^{-E_{34}/kT}+\Omega_{35}e^{-E_{35}/kT}\right\}+A_{31}+A_{32}$$

$$A_4=\frac{C}{\omega_4}\left\{\Omega_{14}+\Omega_{24}+\Omega_{34}+\Omega_{45}e^{-E_{45}/kT}\right\}+A_{41}+A_{42}+A_{43}$$

$$A_5=\frac{C}{\omega_5}\left\{\Omega_{15}+\Omega_{25}+\Omega_{35}+\Omega_{45}\right\}+A_{51}+A_{52}+A_{53}+A_{54}$$

where

$$C=\frac{8.629\times10^{-6}n_e}{T^{1/2}}$$

and

$$B_{32}=n_eq_{32}+A_{32}$$

$$B_{42}=n_eq_{42}+A_{42}$$

$$B_{52}=n_eq_{52}+A_{52}$$

$$B_{43}=n_eq_{43}+A_{43}$$

$$B_{53}=n_eq_{53}+A_{53}$$

$$B_{54}=n_eq_{54}+A_{54}$$

and

$$Q_{145}=A_5q_{14}+B_{54}q_{15},$$

$$Q_{245}=A_5q_{24}+B_{54}q_{25},$$

$$Q_{345}=A_5q_{34}+B_{54}q_{35},$$

$$X_{45}=A_4A_5-B_{54}n_eq_{45},$$

$$AA1=n_eq_{13}A_5X_{45}+B_{43}A_5n_eQ_{145}+B_{53}X_{45}n_eq_{15}+B_{53}n_e^2q_{45}Q_{145},$$

$$AA2=n_eq_{23}A_5X_{45}+B_{43}A_5n_eQ_{245}+B_{53}X_{45}n_eq_{25}+B_{53}n_e^2q_{45}Q_{245},$$

$$AA3=A_3A_5X_{45}-B_{43}A_5n_eQ_{345}-B_{53}X_{45}n_eq_{35}-B_{53}n_e^2q_{45}Q_{345}.$$

Defining the ratios

$$AB13 = AA1/AA3,$$

$$AB23 = AA2/AA3,$$

$$AB14 = [n_e Q_{145} + n_e Q_{345}(AB13)]/X_{45},$$

$$AB24 = [n_e Q_{245} + n_e Q_{345}(AB23)]/X_{45},$$

$$AB15 = \left[n_e q_{15} X_{45} + n_e^2 q_{45} Q_{145} + (AB13)(n_e q_{35} X_{45} + n_e^2 q_{45} Q_{345}) \right] / A_5 X_{45},$$

$$AB25 = \left[n_e q_{25} X_{45} + n_e^2 q_{45} Q_{245} + (AB23)(n_e q_{35} X_{45} + n_e^2 q_{45} Q_{345}) \right] / A_5 X_{45},$$

$$R = \left[\frac{n_e q_{12} + (AB13)B_{32} + (AB14)B_{42} + (AB15)B_{52}}{A_2 - (AB23)B_{32} - (AB24)B_{42} - (AB25)B_{52}} \right],$$

we finally have the following relations for N_1, N_2, N_3, N_4, and N_5:

$$N_1 = \{1 + (AB13) + (AB14) + (AB15) + R[1 + (AB23) + (AB24) + (AB25)]\}^{-1},$$

$$N_2 = RN_1,$$

$$N_3 = N_1(AB13) + N_2(AB23),$$

$$N_4 = N_1(AB14) + N_2(AB24),$$

$$N_5 = N_1(AB15) + N_2(AB25). \tag{A4}$$

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MINAS KAFATOS: Department of Physics, George Mason University, Fairfax, VA 22030

JOHN P. LYNCH: Systems Sciences Division, Computer Sciences Corporation, Department 351, 8728 Colesville Road, Silver Spring, MD 20910