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ON THE FORBIDDEN EMISSION LINES OF IRON IN SEYFERT GALAXIES

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ABSTRACT

The excitation of the [Fe VII], [Fe X], and [Fe XIV] emission lines in Seyfert galaxies is discussed, with special reference to the interpretation of the strengths of these lines in NGC 4151. The [Fe VII] lines probably arise in the same regions as the [Ne V] lines. Newly calculated collision strengths for [Fe VII] are presented, and they are used to find the relative Fe abundance in NGC 4151, approximately $N(\mathrm{Fe})/N(\mathrm{H}) = 1.4 \times 10^{-5}$, with an uncertainty of approximately a factor of 2. The [Fe X] and [Fe XIV] lines may arise in a high-temperature gas, as Oke and Sargent suggested. On this model the amount of high-temperature gas is calculated by using published collision strengths for [Fe XIV] and published plus estimated collision strengths for [Fe X]. The radiation from this high-temperature gas, if it exists, is energetically sufficient to photoionize much of the "cool" gas in which the other observed emission lines are emitted. Thus the hot gas may be the primary source of photoionization. It may be heated by collisions between clouds moving with velocities corresponding to the observed line widths.

I. [Fe VII]

The presence of [Fe VII] emission lines λλ5721, 6087 in NGC 4151 and other Seyfert galaxies has been known since the original work of Seyfert (1943). They arise from the first excited term, ^1D, about 2 eV above the ground ^3F term, and are almost certainly excited by collisions with thermal electrons, just as all the other forbidden lines are. The source of ionization is not quite so certain, but Williams and Weymann (1968) have shown that a photoionization model, in which the input radiation is a plausible power-law continuum, can approximately reproduce all the observed emission-line strengths in NGC 4151 up through [Ne V]. We therefore tentatively adopt this mechanism and work out the implications of the observed [Fe VII] strength.

The ionization potentials of Fe^{5+} and Fe^{6+} have not been directly measured, but their interpolated values as given by Allen (1963), 103 and 130 eV, respectively, are quite close to the ionization potentials of Ne^{3+} and Ne^{4+}, 97.0 and 126.3 eV, respectively. Therefore, under conditions of photoionization the [Fe VII] and [Ne V] lines are emitted in very nearly the same volumes of space, and in these volumes Fe is chiefly Fe^{6+}, while Ne is chiefly Ne^{4+}. Hence to a fairly good approximation the observed relative strengths of [Fe VII] and [Ne V] lines may be used to determine the ratio of abundances of Fe to Ne in this region, and hence presumably (if homogeneity of composition is assumed) throughout the emitting gas in the nucleus of NGC 4151.

We must therefore calculate the emission rate in the [Fe VII] and [Ne V] lines under conditions of collisional excitation. The term energies are listed in Table 1, and it can be seen that in addition to the ^1D term from which λλ5721, 6087 arise, the ^3P (from which λλ5159, 5278, also observed by Seyfert as weak lines in NGC 4151, arise) and ^1G terms are also relatively close to the ground term. But $3d^2$ ^1S and all the terms from other

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configurations are considerably higher and therefore can safely be omitted from the discussion.

The formulae for collisional transition probabilities (per ion in the initial level per unit time) C are

$$C(j \rightarrow i) = \frac{8.63 \times 10^{-6}}{\omega_j T_e^{1/2}} \Omega(i, j) N_e \quad (1)$$

for de-excitation, and

$$C(i \rightarrow j) = \frac{\omega_j}{\omega_i} \exp\left[-(E_j - E_i)/kT_e\right] C(j \rightarrow i) \quad (2)$$

for excitation, in terms of the mean collision strength $\Omega(i, j)$ the statistical weights ω_i, ω_j, and the electron density and temperature N_e, T_e (Seaton 1958). Our first concern before calculating collision strengths was to test whether configuration interaction is important for the terms of $3d^2$. For this purpose a computer program described by

TABLE 1

TERM ENERGIES FOR Fe VII (cm^{-1})

Level	Observed*		Calculated (Present Wave Functions)
$3d^2\ ^3F_2$	0	(1346)	0
$3d^2\ ^3F_3$	1047		
$3d^2\ ^3F_4$	2327		
$3d^2\ ^1D_2$	17475	(17475)	19600
$3d^2\ ^3P_0$	20037	(20860)	23400
$3d^2\ ^3P_1$	20428		
$3d^2\ ^3P_2$	21275		
$3d^2\ ^1G_4$	28915	(28915)	30500
$3d^2\ ^1S$	. . .	. . .	75000
$3d4s\ ^3D$	. . .	. . .	366500
$3d4s\ ^1D$	. . .	. . .	372300

NOTE.—Term energies shown in parentheses are weighted averages of observed level energies listed.

* *Revised Multiplet Table.*

Eissner and Nussbaumer (1969) was used, and the configurations $3d4s$, $3d4d$, and $4s^2$ were added to $3d^2$. None of these other contributions entered the total wave functions with a weight exceeding 0.06, and configuration interaction was therefore neglected.

Collision strengths were calculated in a distorted-wave approximation by using a computer program developed by W. Eissner at University College, London. It uses the same bound-wave functions employed for the calculation of configuration interaction. The free-wave functions were also calculated in a Thomas-Fermi potential, which was chosen so that the bound-wave functions resulting from that same potential minimize the Fe VI ground-term energies. Partial collision strengths were calculated for all quantum numbers that can contribute to the excitation in [Fe VII] (even and odd parity, $S^T = \frac{1}{2}, \frac{3}{2}$, and $0 \leq L^T \leq L^{\max}$, where $L^{\max}$ was increased until convergence was evident—in some cases $L^{\max} = 6$) and summed to find the total collision strengths. They were calculated at energies of 0.19, 0.21, 0.23, 0.25, 0.30, and 0.40 rydbergs above the ground term, but the energy variation of the total collision strengths turned out to be negligible (1 percent). The resulting collision strengths are listed in Table 2. To find a collision strength between individual levels, the collision strength between the terms involved was divided up according to the statistical weights of the levels.

The radiative transition probabilities for [Fe VII], which involve magnetic-dipole probabilities A_m and electric-quadrupole probabilities A_q, were first calculated by Pasternack (1940). The A_q involve the integral

$$\sigma = \int_0^\infty (rP_{3d})^2 dr\,, \tag{3}$$

which was estimated by Pasternack from screening-constant arguments to be $\sigma = 1.5$. Garstang (1964) later corrected Pasternack's A_q by using values $\sigma = 0.80$ or 0.84 calculated from Hartree-Fock bound-wave functions. The bound-wave functions described above give $\sigma = 0.86$, leading to a correction factor of 0.32 to all Pasternack's A_q for [Fe VII]. The resulting total transition probabilities A are listed in Table 3.

TABLE 2

COLLISION STRENGTHS $\Omega(i, j)$ FOR Fe VII

Terms	Collision Strength	Terms	Collision Strength
(i, j)	$\Omega(i, j)$	$^1D, {}^3P$	0.66
$^3F, {}^1D$	1.64	$^1D, {}^1G$	0.43
$^3F, {}^3P$	2.79	$^3P, {}^1G$	1.00
$^3F, {}^1G$	2.42		

TABLE 3

LINE-EMISSION COEFFICIENTS F FOR Fe VII AND Ne V

			$F(10^{-17}$ erg sec$^{-1})$						
				$T_e=1.5\times10^4$,	$T_e=2.0\times10^4$				
TRANSITION	λ (Å)	A (sec^{-1})	$T_e=10^4$, $N_e=10^4$	$N_e=10^4$	$N_e=10^4$	$N_e=10^5$	$N_e=10^6$	$N_e=10^7$	$N_e=10^8$
					[Fe VII]				
$^3F_3$–$^1D_2$	6086.9	0.49	1.47	2.90	3.91	39.0	381	2790	7600
$^3F_2$–$^1D_2$	5721.1	0.30	0.96	1.89	2.54	2.54	248	1810	4950
$^3F_2$–$^3P_0$	4989.0	0.122	0.28	0.61	0.85	8.21	63.9	256	432
$^3F_3$–$^3P_1$	5159.0	0.067	0.35	0.77	1.09	10.7	91.1	398	673
$^3F_2$–$^3P_1$	4893.4	0.046	0.26	0.56	0.79	7.72	65.9	288	487
$^3F_4$–$^3P_2$	5277.7	0.064	0.25	0.57	0.83	8.26	80.9	496	965
$^3F_3$–$^3P_2$	4944.0	0.066	0.28	0.63	0.91	9.10	89.0	546	1060
$^3F_2$–$^3P_2$	4699.8	0.012	0.05	0.12	0.17	1.74	17.0	104	203
$^3F_4$–$^1G_4$	3760.3	0.37	0.48	1.56	2.68	26.8	271	2330	7210
$^3F_3$–$^1G_4$	3587.8	0.26	0.35	1.14	1.97	1.98	200	1710	5310
					[Ne V]				
$^3P_2$–$^1D_2$	3425.9	0.38	0.77	2.65	4.74	48.2	477	3640	10700
$^3P_1$–$^1D_2$	3345.8	0.138	0.29	0.99	1.76	17.9	177	1350	3970
f			1.91	1.09	0.82	0.81	0.80	0.77	0.71

Then to find the emission rates in the individual lines, the statistical equilibrium equations for the relative populations N_i of all the m levels

$$\Sigma_{j\neq i}N_jC(j\rightarrow i) + \Sigma_{j>i}N_jA(j\rightarrow i) = N_i[\Sigma_{j\neq i}C(i\rightarrow j) + \Sigma_{j<i}A(i\rightarrow j)]\,, \quad i = 1, \ldots, m\,, \tag{4}$$

are solved with the normalization

$$\sum_{i=1}^{m} N_i = 1\,. \tag{5}$$

The collision strengths between the levels of ^3F which enter this calculation were estimated, by analogy to the ^3P calculations of Saraph, Seaton, and Shemming (1969), as $\Omega(^3F_2, {}^3F_3) = 0.30$, $\Omega(^3F_2, {}^3F_4) = 0.15$, $\Omega(^3F_3, {}^3F_4) = 0.70$. The resulting calculated rates of line emission depend only very weakly on these numerical values.

The emission rate (per unit volume per unit time) in a particular line $j \rightarrow i$ is then given by

$$E(\text{Fe VII}, j\rightarrow i) = N(\text{Fe}^{6+})N_jA(j\rightarrow i)\Delta E_{ij} = N(\text{Fe}^{6+})F(j\rightarrow i)\,. \tag{6}$$

A completely analogous expression may be written for the emission rates in the [Ne v] lines by using the collision strengths of Saraph, Seaton, and Shemming (1969) and the transition probabilities of Garstang (1968). Some numerical values of F are listed as functions of T_e, N_e in Table 3. It can be seen that the influence of collisional de-excitation (indicated by deviations of F from proportionality to N_e at fixed T_e) is small for $N_e \leq 10^6$ cm^{-3}.

Thus finally fixing our attention on the strongest [Fe VII] and [Ne v] lines, λλ6087 and 3426, respectively, we derive the ratio

$$\frac{I(\lambda 6087)}{I(\lambda 3426)} = \frac{E(\lambda 6087)}{E(\lambda 3426)} = \frac{N(\text{Fe}^{6+})}{N(\text{Ne}^{4+})} f(T_e)\,. \tag{7}$$

The numerical values of $f(T_e)$ are also given in Table 3. Thus from the observed line ratio the relative abundance $N(\text{Fe})/N(\text{Ne})$ can be derived for any assumed temperature under the assumptions discussed above.

The best measured line intensities of a Seyfert galaxy are available for NGC 4151 from the work of Oke and Sargent (1968). This galaxy is not much affected by reddening (Wampler 1968), and the observed intensities can be taken to be essentially the same as the emitted intensities. Oke and Sargent find $I(\lambda 6087)/I(\lambda 5721) = 1.6$, in good agreement with the expected ratio 1.53. The lines [Fe VII] λλ5159, 5278 arising from ^3P were not measured by Oke and Sargent, but were observed by Seyfert as weak lines, and λ5159 is independently confirmed by Weedman (1969). The other lines of the ^3F–^3P multiplet, λλ4989, 4893, 4944, are in the spectral region dominated by the strong Hβ and [O III] lines and would not be expected to be observable. However, it seems from Table 3 that λλ3760, 3587 of the ^3F–^1G multiplet should be observable, which confirms the tentative identification of λ3760 by Anderson and Kraft (1969). In addition, both these lines have been identified on a recent spectrogram of NGC 4151 by Weymann and Williams (1970).

Finally, when [Fe VII] and [Ne v] are compared, the observed ratio $I(\lambda 6087)/I(\lambda 3426) = 0.21$, which corresponds to an abundance ratio $N(\text{Fe})/N(\text{Ne}) = 0.11$ if $T_e = 10000°$, 0.19 if $T_e = 15000°$, or 0.26 if $T_e = 20000°$ K. The temperature is not known, but models of planetary nebulae (Harrington 1968; Flower 1969) have $T_e \approx 17000°$ in the [Ne v] emitting zone, and in the model of a Seyfert galaxy it is probably slightly higher, say $T_e \approx 20000°$. Thus we take $N(\text{Fe})/N(\text{Ne}) = 0.26$, which is considerably higher than the "cosmic abundance" values of this ratio, given, for instance, as 0.029

by Allen (1963) and 0.0081 by Aller (1961). Recent observational research, however, has tended to give increased values of the Fe abundance (Garz *et al.* 1969) and decreased values of the Ne abundance (Harrington 1968; Flower 1969) in at least some well-studied objects, so the Fe/Ne ratio in NGC 4151 may be quite normal. Note, however, that the Ne abundance is low in NGC 4151 according to Williams and Weymann's photoionization model, approximately $N(\mathrm{Ne})/N(\mathrm{H}) = 5.4 \times 10^{-5}$, so $N(\mathrm{Fe})/N(\mathrm{H}) = 1.4 \times 10^{-5}$, where the accumulated uncertainty is probably a factor of 2.

II. [Fe x] AND [Fe xiv]

The [Fe x] λ6374 and [Fe xiv] λ5303 emission lines in NGC 4151 were first identified by Wilson (Oke and Sargent 1968). They can be approximately accounted for on the photoionization model described above, by using the abundance of Fe derived there (Osterbrock 1969). The main difficulty with this interpretation is that, unless somewhat special assumptions are made, λ5303 is predicted to be quite a bit weaker than λ6374, whereas observationally $\lambda5303/\lambda6374 \approx 0.5$.

Oke and Sargent (1968), however, originally proposed the interpretation that the [Fe x] and [Fe xiv] emissions arise in a high-temperature "corona" of NGC 4151, in which Fe is collisionally ionized. We will here tentatively adopt this latter mechanism, and work out the consequences in terms of the amount of high-temperature gas required and the other radiation it would produce.

Under conditons of collisional ionization, Fe^{9+} has its maximum abundance at $T_e = 1.2 \times 10^6$, where $N(\mathrm{Fe}^{+9})/N(\mathrm{Fe}) = 0.33$, and Fe^{+13} has its maximum abundance at $T_e = 2.0 \times 10^6$, where $N(\mathrm{Fe}^{+13})/N(\mathrm{Fe}) = 0.25$, according to the ionization calculations of Jordan (1969), which are fairly well confirmed by those of Allen and Dupree (1969). We could then assume that there is just enough coronal gas present at $T_e = 1.2 \times 10^6$ to explain the observed [Fe x] emission, and enough at $T_e = 2.0 \times 10^6$ to explain the observed [Fe xiv] emission, and calculate on this basis the properties of the required corona of NGC 4151. This assumption seems quite artificial, however, and we think it more reasonable to assume that there is coronal gas with a continuous range of temperatures, and calculate the properties of this distribution required to match the observed line strengths. Another limiting assumption is that all the coronal gas is at the one temperature that matches the observed ratio of line strengths λ5303/λ6374, and we also work out the consequences of this assumption.

Let us first discuss the excitation coefficients for the [Fe x] and [Fe xiv] lines. The transitions involved are $3s^23p^5\ ^2P_{3/2}$–$^2P_{1/2}$ and $3s^23p\ ^2P_{1/2}$–$^2P_{3/2}$, respectively, and the best published values of the collision strengths $\Omega(^2P_{1/2}, {}^2P_{3/2})$ are those of Blaha (1969). In addition, however, collisional excitation occurs from the ground term of $3s^23p^n$ to the higher $3s3p^{n+1}$ and $3s^23p^{n-1}\,3d$ configurations, followed by radiative cascading down to the excited term of $3s^23p^n$ (Pecker and Thomas 1962). Thus the total effective collision strength for excitation, say of Fe xiv $^2P_{3/2}$, can be written

$$\Omega_{\mathrm{eff}}(^2P_{1/2}, {}^2P_{3/2}) = \Omega(^2P_{1/2}, {}^2P_{3/2}) + \Sigma_L \Omega(^2P_{1/2}, L)\, b(L, {}^2P_{3/2}) \exp\left(-\chi_L/kT_e\right)\,, \quad (8)$$

where the sum is over all important upper levels L, $b(L, {}^2P_{3/2})$ is the branching ratio or relative probability that an excitation to L will be followed by radiative decay to $^2P_{3/2}$, and χ_L is the excitation potential of level L. (At $T_e \sim 10^6$ the excitation potential of the $^2P_{3/2}$ level is negligibly small.) The required collision strengths for $L = 3s3p^2\ ^2S_{1/2}$, $^2D_{3/2}$, $^2P_{1/2}$, $^2P_{3/2}$ and $3s^23d\ ^2D'_{3/2}$ have all been calculated by Petrini (1969), and the transition probabilities necessary to calculate the branching ratios are available from Garstang (1962). These values of Ω and b are collected in Table 4. For Fe x, published collision strengths for excitation of the levels of $3s3p^6$ and $3s^23p^43d$ are not available, but f-values are (Garstang 1962; Fawcett, Peacock, and Cowan 1968) and we estimate the collision strength from the approximate relationship (Seaton 1962).

$$\Omega(i, j) = \frac{4\pi}{3} \frac{g_i f(j, i)}{E_j - E_i} \bar{g} , \tag{9}$$

where the energy difference $E_j - E_i$ ($=\chi_L$ in our case) is expressed in atomic units, and $\bar{g}$ is an effective Gaunt factor. We have estimated $\bar{g}$-values for these high stages of ionization of Fe by using equation (9) with the known Ω and f for Fe XIV, and find as mean values $\bar{g}(3s, 3p) = 1$, $\bar{g}(3p, 3d) = \frac{5}{4}$. Values of the Ω calculated for Fe XIV with these effective Gaunt factors are listed in Table 4 (for comparison with the accurately calculated values), and those for Fe X are listed in Table 5. Effective collision strengths as defined by equation (8) (for Fe X, $^2P_{1/2}$ and $^2P_{3/2}$ must be interchanged) are plotted in Figure 1.

TABLE 4

COLLISION STRENGTHS AND BRANCHING RATIOS FOR CASCADE EXCITATION OF Fe XIV

Level L	λ (Å)	Petrini $\Omega(^2P_{1/2}, L)$	Equation (9) $\Omega(^2P_{1/2}, L)$	$b(L, {}^2P_{3/2})$
$3d\ ^2D_{3/2}$	211.3	3.0	3.1	0.21
$3s3p^2\ ^2D_{3/2}$	344	0.82	0.60	0.031
$3s3p^2\ ^2S_{1/2}$	274.3	0.40	1.9	0.042
$3s3p^2\ ^2P_{1/2}$	257.8	2.3	1.3	0.62
$3s3p^2\ ^2P_{3/2}$	251.8	1.2	1.5	0.82

TABLE 5

COLLISION STRENGTHS AND BRANCHING RATIOS FOR CASCADE EXCITATION OF Fe X

Level L	λ (Å)	Equation (9) $\Omega(^2P_{3/2}, L)$	$b(L, {}^2P_{1/2})$
$3s3p^6\ ^2S_{1/2}$	347	3.9	0.32
$3p^4(^3P)3d'\ ^2D_{3/2}$	170.6	0.91	0.93
$3p^4(^3P)3d'\ ^2P_{3/2}$	177.2	11.3	0.038
$3p^4(^3P)3d'\ ^2P_{1/2}$	175.5	1.8	0.69
$3p^4(^1D)3d\ ^2S_{1/2}$	184.5	2.5	0.27

We can now calculate the rates of electron excitation of the [Fe X] and [Fe XIV] forbidden lines. In addition, under coronal conditions, proton excitation is not completely negligible, and for [Fe XIV] the proton cross-section has been calculated by Seaton (1964). The [Fe X] proton cross-section is not available, but to a fairly good approximation we can take the ratio of the rate of proton excitation to the rate of direct electron excitation to be the same function of Z^2/T_e as in [Fe XIV].

The total rate of photon emission in either of the [Fe X] or [Fe XIV] lines is then just equal to the rate of collisional excitation by electrons and protons together, since collisional de-excitation is negligible. The emission rate in, say, [Fe X] λ6374 can thus be written

$$\begin{aligned} E(\text{Fe X}, \lambda 6374) &= N(\text{Fe}^{9+}) N_e \psi(\lambda 6374, T_e) \\ &= N(\text{Fe}) N_e \frac{N(\text{Fe}^{+9})}{N(\text{Fe})} \psi(\lambda 6374, T_e) = N(\text{Fe}) N_e \phi(\lambda 6374, T_e) \end{aligned} \tag{10}$$

since the degree of collisional ionization under coronal conditions depends only on T_e. There is an exactly corresponding expression for E(Fe XIV, λ5303). The degree of ionization $N(\mathrm{Fe}^{+n})/N(\mathrm{Fe})$ is available from the calculations of Jordan (1969), and the resulting emission rates ϕ are listed in Table 6.

We now wish to match the observed λ5303 and λ6374 line strengths in NGC 4151 to the calculated strengths in an assumed model "corona." Since there are only two observed quantities, we could find the amounts of gas required at two arbitrary temperatures, say 1.2×10^6 and 2.1×10^6, the most effective temperatures for emission of [Fe x] λ6374 and [Fe xiv] λ5303, respectively. Instead, it seems more natural to assume that there is a distribution of hot gas with various temperatures, and find the one parameter of the required distribution and the total amount of gas. For simplicity we assume a distribution over a discrete number of temperatures, and write

$$N_e(T)N_{\mathrm{H}}(T_e)V(T_e) = v(T_e) \tag{11}$$

as the electron density, proton density, and effective volume at the temperature T_e; this product determines the total emission at the temperature T_e, and we can write

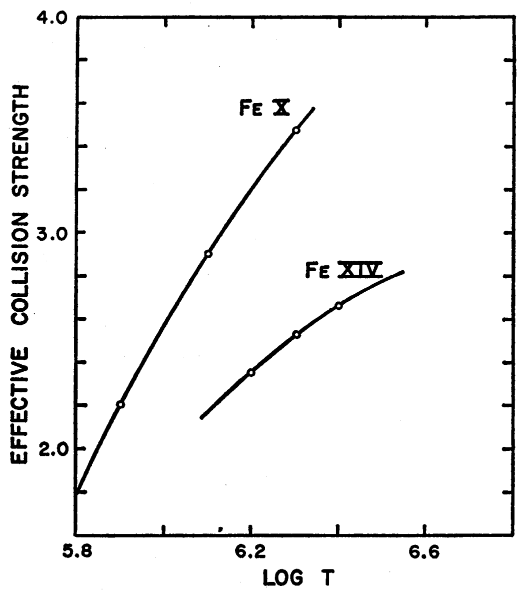

FIG. 1.—Effective collision strengths $\Omega_{\mathrm{eff}}(^2P_{1/2}, {}^2P_{3/2})$ for [Fe x] and [Fe xiv] at high temperatures taking account of cascading from higher levels as in eq. (8).

TABLE 6

Fe Emission-Line Rates under Collisional Ionization and Excitation

log T_e	$E(5303)/N_eN(\mathrm{Fe})$ (ergs cm³ sec⁻¹)	$E(6374)/N_eN(\mathrm{Fe})$ (ergs cm³ sec⁻¹)	$E(\mathrm{total})/N_eN(\mathrm{H})$ (ergs cm³ sec⁻¹)
5.8	...	3.7×10^{-22}	3.2×10^{-22}
5.9	...	1.7×10^{-21}	1.4×10^{-22}
6.0	...	5.1×10^{-21}	8.0×10^{-23}
6.1	9.0×10^{-23}	7.3×10^{-21}	6.0×10^{-23}
6.2	1.8×10^{-21}	3.8×10^{-21}	5.8×10^{-23}
6.3	7.1×10^{-21}	5.6×10^{-22}	5.6×10^{-23}
6.4	4.4×10^{-21}	...	5.1×10^{-23}
6.5	1.1×10^{-21}	...	4.5×10^{-23}
6.6	2.0×10^{-22}	...	3.7×10^{-23}

$$L(\lambda 6374) = \frac{N(\mathrm{Fe})}{N(\mathrm{H})} \Sigma_{T_e} \phi(\lambda 6374, T_e) v(T_e) \, ,$$
$$L(\lambda 5303) = \frac{N(\mathrm{Fe})}{N(\mathrm{H})} \Sigma_{T_e} \phi(\lambda 5303, T_e) v(T_e) \, . \qquad (12)$$

We have assumed a range of temperatures $5.8 \leq \log T_e \leq 6.6$, taken discrete temperatures $\log T_e = 5.8, 5.9, \ldots, 6.6$, assumed a linear distribution function

$$v(T_e) = a + b(\log T_e - 6.0) \, , \qquad (13)$$

and then from the observed luminosities (Oke and Sargent 1968) $L(\lambda 6374) = 1.8 \times 10^{39}$ ergs sec^{-1}, $L(\lambda 5303) = 0.8 \times 10^{39}$ ergs sec^{-1} have found the two constants $a = 8.2 \times 10^{63}$ cm^3, $b = -1.2 \times 10^{64}$ cm^3. This corresponds to a distribution dropping off toward high temperatures, with no gas at temperatures above $T_e \approx 5 \times 10^6$.

Next we may derive two quantities of interest for this assumed high-temperature "corona" in NGC 4151, namely, the total amount of gas and the total radiation it emits. The radiation is easily derived from the calculations of Cox and Tucker (1969), whose results (read off their Fig. 4) are listed as E(total) in Table 6. The total radiation emitted by the hot gas is

$$L(\mathrm{total}) = \Sigma_{T_e} E(\mathrm{total}, T_e) v(T_e) \, , \qquad (14)$$

and by using the above spectrum we find $L(\mathrm{total}) = 6.9 \times 10^{42}$ ergs sec^{-1}. This is considerably larger than the total luminosity emitted by the "cool" gas ($T_e \approx 10^4$) in NGC 4151 in the form of all observed (Oke and Sargent 1968) forbidden lines λλ3425–7330 together, $L_f \approx 4 \times 10^{41}$ ergs sec^{-1}. It is also larger than the total luminosity of all observed Balmer lines together, $L_B \approx 3 \times 10^{41}$ ergs sec^{-1}, and larger even than the lower limit that can be set to Lα from the observed Balmer lines, $L_{\mathrm{L}\alpha} \geq 1.5 \times 10^{42}$ ergs sec^{-1}. The calculations of Cox and Tucker (1969) show that the bulk of the radiation emitted by the hot gas has $\lambda \leq 912$ Å and therefore is ionizing radiation for H, and that some of it has a considerably shorter wavelength and can ionize other ions. Therefore, if this hot "corona" really exists, it is quite conceivable that it is the source of ionizing radiation that excites and ionizes all the cool gas (up to Ne^{4+} and Fe^{6+}) and that no ultraviolet synchrotron source is required. A detailed model similar to that of Weymann and Williams but which used the radiation of a high-temperature plasma as the input radiation field would be necessary to check this possibility in detail. Two possible sources of error should be noted at this point. First, the distribution function of coronal gas has been assumed to extend down to $\log T_e = 5.8$, while the observations of [Fe x] λ6374 actually only *require* (on the collisional model) gas with $\log T_e \gtrsim 6.1$, and in fact the bulk of the radiation comes from regions with temperatures between these two limits. Second, the abundances of heavy elements assumed by Cox and Tucker are different from those derived for NGC 4151; in particular, they have assumed a higher Ne abundance and a good fraction of the calculated radiation comes from Ne VIII around $\log T_e \approx 6$. On the other hand, the elements they have omitted (such as Fe) will add to the ionizing radiation, so again it is clear that a detailed model is the next necessary step.

Next, on this model we can find the total amount of hot gas, but it depends on an assumption about either its volume or its mean density, since the distribution function determines only

$$\langle N_e N_{\mathrm{H}} \rangle V_{\mathrm{eff}} = \Sigma_{T_e} v(T_e) \, , \qquad (15)$$

giving $\langle N_e N_{\mathrm{H}} \rangle V_{\mathrm{eff}} = 5.2 \times 10^{64}$ cm^{-3}. If we assume that the hot gas has uniform density and fills the nucleus with volume $V_n = 1.8 \times 10^{60}$ cm^{-3} (Oke and Sargent 1968), this gives a "corona" with $N_e N_H = 1.7 \times 10^2$ cm^{-3}, not too far from Oke and Sargent's result. Another possibility would be to suppose that the hot gas is of considerably higher density—for example, $N_e = N_H = 1.7 \times 10^4$ cm^{-3}—in which case it would fill a correspondingly smaller volume, $10^{-4}\ V_n$ in the example given. On this picture the hot gas could result from collisions between clouds, leading to heating by shock waves to temperatures as high at 4×10^6 (Osterbrock and Parker 1965; Oke and Sargent 1968). The hot gas could be concentrated in small dense layers between the colliding clouds, rather than in a more nearly uniform "corona." The bulk of the energy of this hot gas would be radiated in the ultraviolet, and absorbed and converted to optical radiation in the cool gas. Detailed models for cloud collisions at relative velocities of the order of 500 km sec^{-1} would be necessary to test this mechanism quantitatively.

As an opposite-extreme assumption to the distribution of temperatures assumed above, we may suppose that all the coronal gas is at a single temperature. This temperature is fixed by the observed intensity ratio $\lambda 5303/\lambda 6374 = 0.5$ (Oke and Sargent 1968), and according to Table 6 it is $\log T_e \approx 6.2$, $T_e \approx 1.6 \times 10^6$. Then the observed luminosities in these two lines give, on this model, $L(\text{total}) = 1.8 \times 10^{42}$ ergs sec^{-1} and $\langle N_e N_H \rangle V_{\text{eff}} = 3.5 \times 10^{64}$ cm^{-3}. Again the calculated radiation of the assumed coronal gas is sufficient to provide the source of ionization of the cool gas.

In summary, the observed [Fe VII] emission lines can be understood as arising from the same gas in a Seyfert galaxy that gives rise to the observed [Ne V] lines. The abundance of Fe is more or less normal. The [Fe X] and [Fe XIV] lines observed in NGC 4151 can arise from photoionization also, if the input radiation source continues to energies greater than 400 eV. Alternatively, they can arise from collisional ionization in a hot gas with temperatures up to $T_e \gtrsim 2 \times 10^6$. This hot gas, if it exists, radiates more energy in the ultraviolet than all the other observed radiation from NGC 4151. It is conceivable that it is the only source of ionizing radiation responsible for the other emission from the nucleus of NGC 4151. It may result from heating in collisions between clouds.

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