THE ASTROPHYSICAL JOURNAL, **238**:10–16, 1980 May 15

O I λ8446 EMISSION IN SEYFERT 1 GALAXIES[1]

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Received 1979 September 14; accepted 1979 November 19

ABSTRACT

Broad O I λ8446 emission is seen in 13 out of 16 observed Seyfert 1 galaxies with strengths compared to Hα ranging from 0.01 to 0.07. λ8446 has no narrow component but is similar in shape and width to the broad component of Hα. Recombination and collisional excitation are easily ruled out as the excitation mechanisms of λ8446 by the lack of observed O I λ7774. Continuum fluorescence is harder to rule out, but assuming case B conditions, the predicted value of λ7990/λ8446 falls significantly above the observed upper limits. Therefore, the excitation mechanism must be Lβ pumping in a Bowen fluorescence process. For this mechanism to be operable, gas must be present with a large population of O I, a source of Lβ photons, and a large optical depth in Hα. A simple uniform-slab model and a somewhat more sophisticated stratified model of a broad-line cloud fail to reproduce the observed λ8446/Hα ratio. However, recent calculations which treat radiative transfer in the lines in a more accurate manner show that deep within the cloud, where H and O are largely neutral, trapped Lα photons will populate the $n = 2$ levels of H (causing large values of $\tau_{H\alpha}$), and Balmer continuum ionization and collisional excitation, combined with ground state ionization due to He diffuse radiation, can produce Lβ photons. Simple calculations show that observed values of λ8446/Hα can be reproduced in this manner; dusty models seem to be ruled out, however. Therefore, these new models of broad-line clouds which were calculated in order to reproduce the observed Lyα/Hα ratios in active nuclei seem to be necessary to reproduce the observed λ8446/Hα ratio as well.

Subject headings: galaxies: Seyfert

One of the more interesting emission lines found in the spectra of gaseous nebulae is O I λ8446 ($3s\ ^3S^0$–$3p\ ^3P$). This permitted line is not excited by the usual physical processes of recombinations or collisions with electrons. It has been discussed in the context of the Orion nebula (Morgan 1971; Grandi 1975*a*, *b*), planetary nebulae (Grandi 1976), and Nova Cygni 1975 (Strittmatter *et al.* 1977). Its presence has also been noted in such interesting emission-line objects as SS 433 (Margon *et al.* 1979), Lk Hα-101 (Herbig 1971), and MWC 349 (Thompson *et al.* 1977). O I λ8446 has also been observed (at lower resolution than reported here) in active extragalactic objects such as NGC 4151 (Netzer and Penston 1976), II Zw 136, I Zw 1, 3C 273 (Oke and Shields 1976), and 3C 120 (Shields, Oke, and Sargent 1972).

On the basis of these latter observations and the questions they raised regarding the excitation mechanism of O I λ8446 in active galactic nuclei, the λ8446 region in the spectra of several Seyfert galaxies was observed. In § I of this paper, the observational data will be discussed. In § II, the excitation mechanism of O I λ8446 in Seyfert galaxies will be discussed, and in § III, O I λ8446 emission in the context of the astrophysics of active nuclei will be considered.

[1] *Lick Obs. Bull.*, No. 857.

I. OBSERVATIONS

Far-red spectral scans (covering, in general, the range $\lambda\lambda$6500–8750) were taken of several Seyfert galaxies using the Lick Observatory Image-Tube Scanner (ITS) (Robinson and Wampler 1972; Miller, Robinson, and Wampler 1976) attached to the Shane 3 m telescope on Mount Hamilton. These scans were taken through an aperture of 2″.7 × 4″, resulting in a spectral resolution of approximately 10 Å. The data were reduced to absolute energy units in a standard manner (Osterbrock and Miller 1975; Costero and Osterbrock 1977). However, since λ8446 is redward of the last calibrated point in the flux standard stars (Stone 1977), the ITS absolute response function is obviously more uncertain here than at lower wavelengths. To first order, the atmospheric absorption bands of O_2 and H_2O that infest the observed spectral range were canceled out by division by early-type standard stars.

A typical ITS spectrum of Akn 564 is reproduced in Figure 1. The scan clearly shows O I λ8446 emission on the long-wavelength side. Three other program scans (used to illustrate the presence of [Fe XI] λ7892) are plotted as Figure 1 of Grandi (1978).

Several other Seyfert galaxies were observed with the Steward Observatory SIT digital TV system (Gilbert *et al.* 1975, 1976; Gilbert, Angel, and Grandi

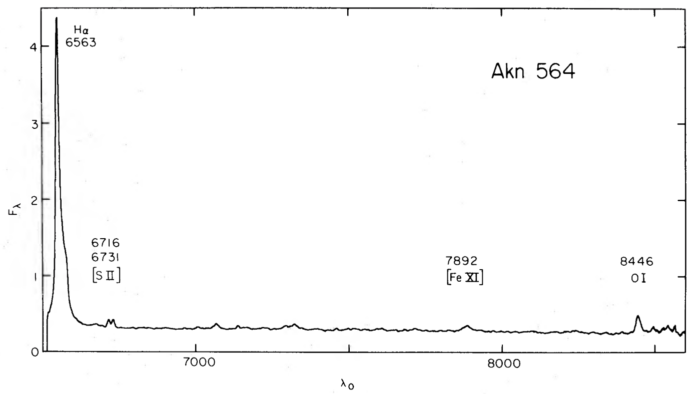

FIG. 1.—Far-red ITS scan of the Seyfert 1 galaxy Akn 564. The scan has been shifted to a rest wavelength scale.

1976) attached to the Cassegrain spectrograph of the Steward Observatory 2.3 m reflector. The SIT scans were reduced in a similar manner as the ITS scans.

Three Seyfert 2 galaxies were observed: NGC 1068 (see Fig. 1 of Grandi 1978), NGC 6764, and Mrk 3. O I λ8446 was not detected in any of these objects. A conservative upper limit for the three objects is $\lambda 8446/\mathrm{H}\alpha \leq 0.005$.

The observed O I $\lambda 8446/\mathrm{H}\alpha$ ratio (or an upper limit) for 16 Seyfert 1 galaxies is listed in Table 1. The galaxies are listed in decreasing order of O I $\lambda 8446/\mathrm{H}\alpha$. A colon after the line strength indicates a particularly uncertain value. For completeness, previous observations of λ8446 in five active nuclei taken from Netzer and Penston (1976), Oke and Shields (1976), and Shields, Oke, and Sargent (1972) are listed on the bottom of Table 1. The data for these latter objects were all taken at much lower resolutions than my data; the resulting $\lambda 8446/\mathrm{H}\alpha$ ratios are therefore probably less reliable.

TABLE 1

O I λ8446 IN SEYFERT 1 GALAXIES

Galaxy	O I $\lambda 8446/\mathrm{H}\alpha$	FWHM (km s^{-1}) Hα	FWHM (km s^{-1}) O I λ8466
NGC 4051	0.069:	1300	1200:
Mrk 486	0.064	2000	...
Mrk 40	0.064:	2000	...
Mrk 42	0.060	550	...
NGC 3516	0.056:	4300	...
3C 120	0.047	2000	2800
NGC 5548	0.045	3300	5500:
Akn 564	0.042	620:	430:
NGC 3227	0.038	2400	...
NGC 7469	0.036:	1700	2800:
Mrk 335	0.025	1700	700
NGC 4151	0.024	3900	3600
III Zw 77	0.008	725	...
Mrk 506	$\leq$0.006	3400	...
Akn 202	$\leq$0.005	1800	...
Mrk 79	$\leq$0.003	5200	...
3C 273	0.10	...	...
I Zw 1	0.092	...	...
II Zw 136	0.056	...	...
3C 120	0.050	...	...
NGC 4151	0.029	...	...

Mrk 42 was included as a Seyfert 1 galaxy for the reasons cited in Phillips (1978): despite its narrow permitted lines, Mrk 42 exhibits definite Seyfert 1 characteristics. Another interesting, not to say unique, Seyfert 1 galaxy, Mrk 231, was also observed as a part of this program. Mrk 231 does show a broad emission line near rest wavelength λ8500 (with a strength compared to Hα of 0.12), but the line peaks significantly to the red of λ8446. Boksenberg *et al.* (1977) identify this line as the Ca II infrared triplet (the strongest component of the triplet is λ8542) with a strength measured from their data of 0.21 times Hα. My data indicate that the line in Mrk 231 near λ8500 lies considerably to the blue of an expected Ca II blend. Perhaps the Mrk 231 feature represents a combination of O I and Ca II, but in any case it is unique among my sample of Seyfert galaxies.

Generally, the O I λ8446 lines discovered in the collection of Seyfert 1 galaxies are rather weak. Hence, profile and width measurements are correspondingly uncertain. For the best cases, a value of the rest frame full width at half-maximum (FWHM) for O I λ8446 is listed in Table 1. For comparison, Table 1 also contains the rest frame FWHM for Hα. These values are mostly taken from Osterbrock (1977) and Phillips (1978). In general, the O I λ8446 line widths are comparable with the Hα width but with a large scatter that is probably dominated by observational error.

Perhaps the best determined λ8446 profile in the observed Seyferts is for NGC 4151. The observed O I λ8446 profile for this object is plotted in Figure 2 on the same velocity scale as the *broad* component of Hα (as plotted in Osterbrock and Koski 1976; this profile has been stripped of narrow components). The profiles appear quite similar. Note, however, that λ8446 in NGC 4151 lacks the strong, narrow component that characterizes the other permitted lines in NGC 4151. NGC 5548 is another Seyfert 1 galaxy containing strong, narrow, permitted line components (NGC 4151 and NGC 5548 are referred to as Seyfert 1.5 galaxies by Osterbrock 1977). The λ8446 profile in this object also lacks a narrow component; therefore, from

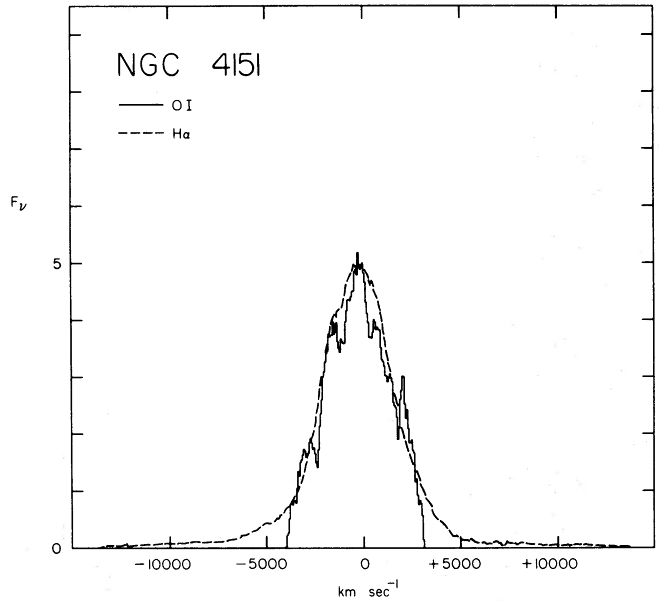

FIG. 2.—A comparison of the O I λ8446 profile and the broad component of Hα (shorn of narrow components and blended lines) of NGC 4151.

the observed lack of narrow O I λ8446 in Seyfert 1.5 galaxies and in Seyfert 2 galaxies, I conclude that O I λ8446 is purely a broad-line phenomenon. Furthermore, the agreement in line profiles between Hα and O I λ8446 implies that the same ensemble of individually optically thick emission-line clouds produces λ8446 as produces Hα. This fact makes less plausible those models which propose an extensive region of neutral clouds (outside optically thin photoionized clouds) where λ8446 emission is excited by continuum fluorescence (Oke and Shields 1976).

Other permitted O I emission lines can be useful diagnostics for understanding the λ8446 emission process in Seyfert galaxies (see § II). O I λ7774 ($3s\ ^5S^0$–$3p\ ^5P$) is the quintet counterpart of λ8446 and has been observed in the spectra of emission-line stars (Andrillat and Swings 1976). λ7254 ($3p\ ^3P$–$5s\ ^3S^0$) and λ7990 ($3p\ ^3P$–$3s'\ ^3D^0$) are higher-excitation feed lines to λ8446 (see Fig. 3). λ7254 has been observed in the Orion nebula (Grandi 1975*b*) and Lk Hα-101 (Herbig 1971). In none of the Seyfert galaxies included in my sample were these, or any other permitted O I lines, observed. Upper limits compared to λ8446 for λλ7774, 7990, and 7254 are listed in Table 2 for the best-observed Seyfert galaxies. Unfortunately, another useful line, λ7002 ($3p\ ^3P$–$4d\ ^3D^0$), is too close to broad He I λ7065 to measure a reliable upper limit.

In some QSOs the O I ultimate resonance line, λ1302, has been observed (Osmer and Smith 1976; Baldwin and Netzer 1978). In the spectrum of 3C 273, in fact, both λ1302 (Boksenberg *et al.* 1978) and λ8446 (Oke and Shields 1976) have been observed. As is discussed in Netzer and Davidson (1979), λ1302/λ8446 should be a valuable reddening indicator for the *broad*-line gas of active nuclei. As can be seen in Figure 3, every λ8446 emission (independent of the excitation mechanism) will result in a λ1302 photon, and since

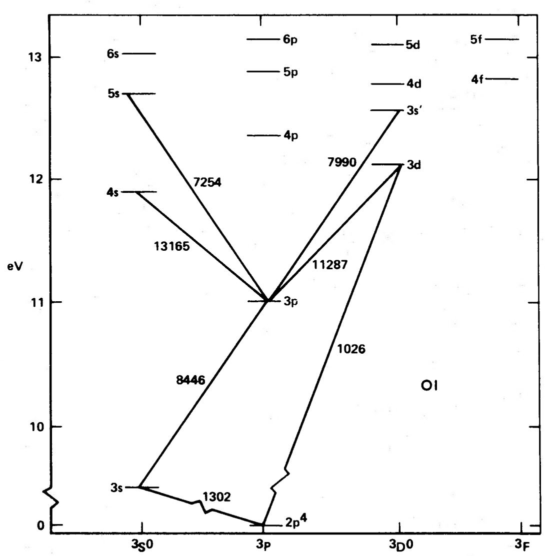

FIG. 3.—Energy level diagram of the triplet states of O I

TABLE 2

O I PERMITTED LINE UPPER LIMITS

Object	λ7774/λ8446	λ7990/λ8446	λ7254/λ8446
NGC 4151	≤0.02	≤0.04	≤0.08
NGC 5548	≤0.06	≤0.02	≤0.05
Mrk 42	≤0.08	≤0.03	≤0.03
Mrk 335	≤0.04	≤0.02	≤0.01
Akn 564	≤0.03	≤0.02	≤0.04

cascades directly to $3s\ ^3S^0$, bypassing λ8446, are rare, as are collisional excitations of λ1302, there should be approximately equal numbers of photons in λ1302 and λ8446. Thus the true unreddened value of the line ratio should be λ1302/λ8446 = 6.5. Hopefully, UV observations of the Seyfert 1 galaxies discussed in this paper will soon be available so that observed values of λ1302/λ8446 may be measured and reddenings determined.

To summarize this section on the observational data: O I λ8446 is seen in 13 out of 16 observed Seyfert 1 galaxies with strengths compared to Hα ranging from 0.01 to 0.07. λ8446 has no narrow component but is similar in shape and width to the broad component of Hα. Other permitted lines of O I such as λλ7774, 7990, and 7254 are not seen (with upper limits 0.01–0.08 of λ8446) in the Seyfert galaxy spectra.

II. EXCITATION MECHANISM

What is the excitation mechanism of the broad O I λ8446 emission observed in Seyfert galaxies? Recombination, collisional excitation by electrons, and continuum fluorescence are possible excitation processes, as is a fluorescence mechanism due to a coincidence of energy levels between H I and O I. Because of this coincidence (Bowen 1947), Lβ λ1025.72 corresponds to and can pump the O I ground-state resonance line $2p^4\ ^3P_2$–$3d\ ^3D^0$ λ1025.77; the wavelength difference is approximately one thermal Doppler width of Lβ at 10^4 K.

The tools that can be used to distinguish between these various mechanisms are the presence or absence of lines of O I other than λ8446. For example, the case for starlight continuum fluorescence as the excitation mechanism for O I λ8446 in the Orion Nebula was proved by the presence of O I lines such as λ7254 and λ7002 (Grandi 1975*a*, *b*) and the strength of λ13165 (Lowe, Moorhead, and Wehlau 1977). On the other hand, in the envelope of Nova Cygni 1975, the large strength of λ11287 and the absence of λ13165 indicate that Lβ fluorescence of the $3d\ ^3D^0$ level of O I is the pumping mechanism for λ8446 (Strittmatter *et al.* 1977).

Although observations of the very useful diagnostic lines λ11287 and λ13165 in Seyfert 1 galaxies seem to be beyond the current state of observational art, the upper limits derived in the previous section for λλ7774, 7990, and 7254 can be used to deduce the relevant excitation process of O I λ8446.

The upper limits to the strength of λ7774 (the quintet counterpart to λ8446) listed in Table 2 rule out recombination and collisional excitation by electrons as excitation mechanisms of λ8446. Based solely on relative statistical weights, the relative strength due to recombination should be λ7774/λ8446 ≈ 1.7. If collisional excitation excites λ8446, then λ7774/λ8446 ≈ 0.3 using the collisional cross sections from the ground state (at $T_e = 10^4$ K) of Haisch *et al.* (1977).

It is more difficult to deduce the relevant excitation process for λ8446 from among the remaining two contending processes: continuum or Lβ fluorescence. Basically, as discussed above, continuum fluorescence implies the presence of lines such as λ7254 and λ7990, while Lβ fluorescence implies their absence (see Netzer and Penston 1976). I have calculated relative λ7254/λ8446 and λ7990/λ8446 line strengths assuming that the O I atoms are excited solely by continuum fluorescence from an incident power-law spectrum. Twenty-one levels of O I (up to $7d\ ^3D^0$) were considered. Transition probabilities were taken (in order of preference) from Pradhan and Saraph (1977), Weise, Smith, and Glennon (1966) and Kelly (1964) (see also Christensen 1979). In analogy with standard hydrogen-line decrement calculations, two limiting assumptions are made in the O I analysis: case A, which assumes that the O I gas is optically thin in its resonance lines; and case B, which assumes optically thick resonance lines. The results of the O I calculation are listed in Table 3.

TABLE 3

CONTINUUM FLUORESCENCE CASCADE CALCULATION

Case	λ7990/λ8446	λ7254/λ8446
A...........................	0.0030	0.036
B...........................	0.052	0.025

By comparing the values in Tables 2 and 3, it is apparent that although the λ7254/λ8446 ratio is not conclusive, the observed λ7990/λ8446 upper limits can rule out continuum fluorescence as the excitation mechanism if the case B assumption is correct. In fact, two reasons lead to the conclusion that case B is the correct approach.

First, the emissivity of λ8446 is ~10 times higher under case B than case A, which implies that λ8446 emission from optically thick gas will dominate emission from similar amounts of optically thin gas. Second, models of broad-line emission regions (see § III) lead to estimates of the optical depth in Lα of $\tau_{L\alpha} = 10^{5-7}$ to regions where oxygen is neutral. The corresponding optical depths in λ1302, the ultimate resonance line of O I, are $\tau_{\lambda 1302} = 10^{1-3}$, thus confirming the case B assumption.

To summarize this discussion: recombination and collisional excitation are easily ruled out as the excitation mechanism of λ8446 by the lack of observed λ7774. Continuum fluorescence is harder to rule out, but assuming case B conditions, the predicted value of λ7990/λ8446 falls significantly above observed upper limits. Therefore, the one remaining excitation mechanism is Lβ fluorescence.

III. Lβ FLUORESCENCE IN ACTIVE NUCLEI

Having eliminated the alternatives, I turn to the question of how Lβ pumped O I λ8446 emission of the observed strength can be understood in the context of realistic models of the broad-line regions of active nuclei. This problem has been previously addressed by

Netzer and Penston (1976) and Oke and Shields (1976). First, a simple relation for the intensity ratio $\lambda 8446/\mathrm{H}\alpha$ will be derived and, for illustration, it will be applied to a naive model of a broad-line emission cloud as a uniform slab. Next, the derived insights will be extended to more realistic models of broad-line emission clouds.

Aside from explaining the coexistence of O I and $\mathrm{L}\beta$ photons, the basic problem in understanding significant production of $\lambda 8446$ by $\mathrm{L}\beta$ fluorescence is the confinement of $\mathrm{H}\alpha$ photons. In gas typical of H II regions where there is insignificant optical depth in $\mathrm{H}\alpha$, a $\mathrm{L}\beta$ photon will be converted into an $\mathrm{H}\alpha$ photon, which then escapes, after ~ 10 scatterings; whereas, even if all the O is neutral, $\sim 5 \times 10^4$ scatterings off of neutral H are required before $\mathrm{L}\beta$ will excite an O I atom (assuming a cosmic abundance $\mathrm{O/H} = 6 \times 10^{-4}$). Therefore, $\lambda 8446$ emission can only be excited by $\mathrm{L}\beta$ fluorescence in a gas that is optically thick in $\mathrm{H}\alpha$.

Following Netzer and Penston, the fact that both $\mathrm{H}\alpha$ and the $\mathrm{L}\beta$ photons that can pump O I $\lambda 8446$ come from the $n = 3$ levels of H I can be exploited to obtain a relation between $\mathrm{H}\alpha$ and O I $\lambda 8446$. First, I write down an equation giving the statistical equilibrium of $\mathrm{L}\beta$:

$$N_{3p} A_{\mathrm{L}\beta}(1 - \epsilon_{\mathrm{L}\beta}) = N_{1s} \frac{g_{3p}}{g_{1s}} A_{\mathrm{L}\beta} \eta_{\mathrm{L}\beta} , \qquad (1)$$

where N_{3p} and N_{1s} are the number densities of neutral hydrogen atoms in the $3p$ and $1s$ states, g is a statistical weight, ϵ is an escape probability, A is a transition probability, and η is a photon occupation number (see Krolik and McKee 1978). Therefore,

$$\eta_{\mathrm{L}\beta} = (1 - \epsilon_{\mathrm{L}\beta}) \frac{1}{3} \frac{N_{3p}}{N_{1s}} . \qquad (2)$$

The intensity of O I $\lambda 8446$ caused by $\mathrm{L}\beta$ fluorescence will be

$$I_{8446} = \eta_{\mathrm{L}\beta} N_{\mathrm{Og}} \cdot \frac{g_{3d^3D}}{g_{\mathrm{Og}}} A_{1026} \frac{A_{11287}}{A_{11287} + A_{1026}} h\nu_{8446} . \qquad (3)$$

Now, if the levels of the $2p^4\,{}^2P$ ground state of O I (denoted by Og) are in thermodynamic equilibrium, if essentially all of the H and O atoms are in their ground state, if $(1 - \epsilon_{\mathrm{L}\beta}) \approx 1$ (i.e., the gas is optically thick in $\mathrm{L}\beta$), if equation (2) is used to eliminate $\eta_{\mathrm{L}\beta}$ and if the appropriate atomic constants are substituted into equation (3) then

$$I_{8446} = 1.2 \times 10^{-5} N_{3p} \frac{N_{\mathrm{O\,I}}}{N_{\mathrm{H\,I}}} . \qquad (4)$$

Similarly,

$$I_{\mathrm{H}\alpha} = \epsilon_{\mathrm{H}\alpha}(A_{3s\to 2p} N_{3s} + A_{3p\to 2s} N_{3p} + A_{3d\to 2p} N_{3d}) h\nu_{\mathrm{H}\alpha} . \qquad (5)$$

Assuming l-state equilibrium in the $n = 3$ level of H,

$$I_{\mathrm{H}\alpha} = 4.0 \times 10^{-4} N_{3p} \epsilon_{\mathrm{H}\alpha} . \qquad (6)$$

Finally, the ratio of $\lambda 8446$ to $\mathrm{H}\alpha$ can be derived from equations (4) and (6):

$$\lambda 8446/\mathrm{H}\alpha = I_{8446}/I_{\mathrm{H}\alpha} = 3.0 \times 10^{-2}/\epsilon_{\mathrm{H}\alpha}(N_{\mathrm{O\,I}}/N_{\mathrm{H\,I}}) . \qquad (7)$$

If O has a cosmic abundance and the gas is of low ionization so that O is not ionized above O^+, then due to change exchange, $N_{\mathrm{O\,I}}/N_{\mathrm{H\,I}} \approx N_{\mathrm{O}}/N_{\mathrm{H}} = 6 \times 10^{-4}$ and equation (7) becomes

$$\lambda 8446/\mathrm{H}\alpha = 1.8 \times 10^{-5}/\epsilon_{\mathrm{H}\alpha} . \qquad (8)$$

(Netzer and Penston derive a constant of 2.4×10^{-5} in their version of eq. [8].)

To evaluate $\epsilon_{\mathrm{H}\alpha}$, I first assume that our model broad-line cloud (only one of many such optically thick clouds at varying velocities that comprise the broad-line region) is in the form of an infinite slab with a uniform distribution of emitters which is photoionized from one side. To derive values of $\epsilon_{\mathrm{H}\alpha}$, the escape probability formalism of Capriotti (1965) which gives $\epsilon_{\mathrm{H}\alpha}$ as a function of $\tau_{\mathrm{H}\alpha}$ is used. For a fixed value of $\tau_{\mathrm{L}\alpha}$, $\tau_{\mathrm{H}\alpha}$ depends mostly on the incident UV flux which causes populations of $n = 2$ vis recombination (Krolik and McKee 1978; Netzer 1977). This UV flux can be expressed in terms of Γ, the ratio of ionizing photon to electron density (Krolik and McKee 1978). Assuming that the population of $n = 2$ is set by the balance of recombination in and $\mathrm{L}\alpha$ emission out, Krolik and McKee find that (assuming an $\alpha = 1$ power law):

$$\tau_{\mathrm{H}\alpha} \approx 9.0 \times 10^{-9} \Gamma (N_e/10^8) \tau_{\mathrm{L}\alpha}{}^2 . \qquad (9)$$

Thus the ratio $I_{8446}/I_{\mathrm{H}\alpha}$ is reduced to a function of the fundamental ionized slab parameters $\tau_{\mathrm{L}\alpha}$, Γ, and N_e. Realistic values of these parameters are $\tau_{\mathrm{L}\alpha} \approx 4 \times 10^6$ (corresponding to $\tau_{\mathrm{Ly\,cont.}} \approx 500$ at $T_e = 10^4$ K), $N_e \approx 5 \times 10^9\ \mathrm{cm}^{-3}$, and $\Gamma \approx 10^{-2}$ (Mathews, Blumenthal, and Grandi 1980). Under these conditions, oxygen is ionized to the point such that (assuming $\mathrm{O/H} = 6 \times 10^{-4}$) $N_{\mathrm{O\,I}}/N_{\mathrm{H\,I}} \approx 1.4 \times 10^{-6}$. Thus, from equation (9), $\tau_{\mathrm{H}\alpha} \sim 7 \times 10^4$, and from equation (7) (again using Capriotti's 1965 escape probabilities), $\lambda 8446/\mathrm{H}\alpha \approx 0.0015$.

Thus the simple model for the broad-line region of an active galaxy leads to a predicted $\lambda 8446/\mathrm{H}\alpha$ a factor ~ 20 less than the observed value. Basically, this is because O is multiply ionized in the uniform slab calculation, and while there are numerous $\mathrm{L}\beta$ photons capable of pumping O I $\lambda 8446$, there is little, if any, O I to be pumped.

Obviously, a realistic optically thick broad-line emission cloud having $\tau_{\mathrm{L}\alpha} \sim 4 \times 10^6$ is not well represented by a uniform slab. Thus the above prediction should not be taken too seriously. Rather, I might suppose that a collection of uniform slabs could better represent the emission-line cloud. Thus slabs close to the edge of the cloud will have little O I, while slabs close to the neutral edge will be predominantly O I.

The recipe for predicting $\lambda 8446/\mathrm{H}\alpha$ in this composite cloud is to calculate $\tau_{\mathrm{H}\alpha}$ from equation (9) for the values of Γ and N_e corresponding to each slab, and to use this value along with the slab value of $N_{\mathrm{O\,I}}/N_{\mathrm{H\,I}}$ in equation

(7) to derive the slab value of $\lambda 8446/\mathrm{H}\alpha$ (using escape probabilities derived by G. R. Blumenthal [1979, private communication] corresponding to emitters confined to the central plane of each slab). Finally, these ratios are weighted by the slab values of $I_{\mathrm{H}\alpha}$ (determined by the traditional recombination expression plus collisional excitation) to derive the composite value of $\lambda 8446/\mathrm{H}\alpha$. I have used an ionization program (partially described in Grandi 1976 and Grandi and Hawley 1978) to make a composite slab calculation, including the rapid-charge-exchange process O II + H I $\rightleftarrows$ O I + H II and diffuse radiation in the on-the-spot approximation. The final derived value (again assuming $\mathrm{O/H} = 6 \times 10^{-4}$) is $\lambda 8446/\mathrm{H}\alpha = 1.2 \times 10^{-5}$, far below the observed value. An analysis of the individual slabs indicates that in slabs close to the ionized edge of the cloud there is a large production rate of Hα (which also implies a large excitation rate of the $n = 3$ level) but very little O I, while in slabs close to the neutral edge O is totally neutral but there is no excitation of $n = 3$. Therefore, the $\lambda 8446$ emission rate is low in both regions.

Thus a nonuniform model of a broad-line emission cloud made up of several slabs front-to-back does not predict the observed value of $\lambda 8446/\mathrm{H}\alpha$. This same failure was noted by Oke and Shields (1976), who suggest that the requisite combination of neutral H (to give a large $\tau_{\mathrm{H}\alpha}$ and imply a large O I population) and ionized H (to generate Lβ photons to pump $\lambda 8446$) can be found only in a cloud undergoing time-dependent ionization. Fortunately, it seems that a major failing of models such as the composite slab described above—the lack of proper consideration of radiative transfer in the spectral lines—may be much more important in explaining the observed $\lambda 8446/\mathrm{H}\alpha$ than hypothetical time-dependent effects.

Recent (Ferland and Netzer 1979; Kwan and Krolik 1979) attempts at modeling Seyfert 1 and QSO emission-line clouds, mostly motivated by the hope of understanding the observed value of Lα/Hα, have shown that new effects arise from detailed radiative transfer calculations. Assuming a radiation-bounded emission cloud, Ferland and Netzer (1979) have found that population of the $n = 2$ levels of hydrogen, hence $\tau_{\mathrm{H}\alpha}$, is concentrated deep within the cloud, as a result of trapping (and some collisional excitation) of Lα. Although the vast majority of Lα photons are formed close to the ionized edge of the cloud, many of them migrate to regions of large $\tau_{\mathrm{L}\alpha}$, get trapped, and excite the predominantly neutral H into the $n = 2$ level. Even though Lyman continuum photons from the incident photoionizing source are absorbed before reaching these locations deep in the cloud, Balmer continuum photons can penetrate and ionize H atoms in the $n = 2$ level. Ground-state ionization of H can also occur due to line (chiefly He II $\lambda 304$ and He I $\lambda 584$) and continuum radiation from recombining He ions which were photoionized by X-rays. Thus recombinations from these ionizations, combined with collisional excitation from the H atoms in the $n = 2$ level, should provide copious Lβ photons. Therefore, the three requirements for production of O I $\lambda 8446$ by Lβ fluorescence are simultaneously present in a partially ionized region deep in the emission-line cloud: Lβ photons, O I atoms, and a large value of $\tau_{\mathrm{H}\alpha}$.

Following the formalism of Ferland and Netzer (their eqs. [9]–[12] and Table 1) applied to parameters given above for a power-law ionized cloud ($N_e = 5 \times 10^9$ and $\Gamma = 10^{-2}$), $\tau_{\mathrm{H}\alpha}$ deep inside the cloud will be $\tau_{\mathrm{H}\alpha} \approx 2000$ (note that the "total" rather than the "effective" value of $\tau_{\mathrm{H}\alpha}$ is relevant to O I $\lambda 8446$ production). This will result in (from eq. [8] and Capriotti's 1965 escape probabilities) $\lambda 8446/\mathrm{H}\alpha \approx 0.02$, in reasonable agreement with observations. Of course, I must still integrate the total Hα intensity over the whole cloud and not just the region deep inside (this is where the stratified slab calculation of $\lambda 8446/\mathrm{H}\alpha$ fails); but (again according to Ferland and Netzer) the Hα formed deep in the cloud along with $\lambda 8446$ is ~ 4 times stronger than the Hα excited by recombination in more-ionized regions of the cloud. Hence, $\lambda 8446/\mathrm{H}\alpha \approx 0.02$ is also a reasonable estimate for the intensity ratio from the complete cloud.

It is interesting to note that cloud models such as those I have just discussed predict values of Lα/Hα much closer to the observed value than predictions from uniform slabs. Therefore, a consistent model of a broad emission line cloud seems to be emerging that can explain several of the odd features seen in active nuclei. Hopefully, more detailed calculations will lead to a model which can reproduce not only the observed $\lambda 8446/\mathrm{H}\alpha$ and Lα/Hα but also Mg II/Hα (Grandi and Phillips 1979) and possible Balmer continuum emission (Grandi and Phillips 1980). Both of these latter spectroscopic effects are also very sensitive to changes in conditions in the transition zone deep within the cloud.

A completely self-consistent calculation of a cloud must couple Lβ fluorescence of O I into a model atom for H. At sufficiently high $\tau_{\mathrm{H}\alpha}$, Hα and Lβ photons will be destroyed quicker by fluorescence of O I than by escape of Hα. Thus, because of the presence of the O I drain, the statistical equilibrium of H might be significantly affected. I calculate that for $\tau_{\mathrm{H}\alpha} \gtrsim 2 \times 10^4$ (for $\mathrm{O/H} = 6 \times 10^{-4}$), the loss rate from $n = 3$ due to O I fluorescence equals the loss rate due to Hα escape. This effect would probably result in larger than expected values of Lα/Hα, although the situation at very high $\tau_{\mathrm{H}\alpha}$ is not obvious.

The presence of internal dust in a broad line emission region has sometimes been postulated in order to explain such anomalies as the observed ratio Lα/Hα. What impact would internal dust have on the model of O I $\lambda 8446$ emission discussed above? I suggest three possible effects: destruction of Lβ photons before they can pump O I atoms, destruction of Lα photons so that large $n = 2$ populations are suppressed, and destruction of high-energy photons so that extended, partially ionized regions are truncated.

Using the dust opacity listed in London (1979), I find the dust absorption of Lβ to be negligible compared to O I absorption even for extremely large dust-to-gas ratios. The other two effects seem to be more important, however. Ferland and Netzer (1979) calculate, for a dust-to-gas ratio of 0.1 times the galactic value, that 86% of the Lα photons produced are destroyed by dust absorption, rising to 96% for a galactic dust-to-gas ratio. Also, fewer Lα photons are produced. Ferland and Netzer show that for $\tau_{\rm dust}(L\alpha) \geq 0.3$ (corresponding to a dust-to-gas ratio somewhat less than galactic) the gas can be considered to be ionized by a blackbody (since the high-energy photons are preferentially destroyed by the dust). In this case, $\tau_{H\alpha}$ will be reduced almost an order of magnitude from the value calculated above, reducing the predicted λ8446/Hα ratio far below observed values. Also, as shown by Baldwin and Netzer (1978), the blackbody-like ionization structure results in a sharp truncation of the partially ionized region which produces collisionally excited Lα. Thus it seems unlikely that even moderate amounts of dust are present in active nuclei if the observed value of λ8446/Hα in Seyfert 1 galaxies are typical of all such objects. Baldwin and Netzer, however, demonstrate that dusty models provide a better match than dustless models to other line ratios in QSO spectra.

To summarize this section: An equation is derived (eq. [7]) which relates λ8446/Hα to only $N_{\rm O\,I}/N_{\rm H\,I}$ and the escape probability of Hα photons, $\epsilon_{H\alpha}$. Application of this formula to a simple uniform-slab model of a broad line emission region fails to reproduce the observed λ8446/Hα ratio because O is multiply ionized. A more sophisticated model of several uniform slabs stacked front-to-back also fails to reproduce the observed λ8446/Hα since in neutral regions, where O I is predominant and $\tau_{H\alpha}$ is large, there is very little excitation of Lβ photons, and in ionized regions, where Lβ photons are common, O is multiply ionized. However, recent calculations (Ferland and Netzer 1979; Kwan and Krolik 1979), which treat radiative transfer in a more accurate manner, show that deep within the cloud, where H and O are largely neutral, trapped Lα photons will populate the $n = 2$ levels of H, and Balmer continuum ionization and collisional excitation by electrons (a result of ionizations by diffuse He radiation) will produce Lβ photons. Simple calculations show that observed values of λ8446/Hα can be reproduced in this manner, but even moderate amounts of internal dust seem to be ruled out. Therefore, these new models of broad emission line clouds which were calculated in order to try to reproduce the observed Lα/Hα ratios in active nuclei seem to be necessary to reproduce the observed λ8446/Hα ratio as well.

I wish to thank D. E. Osterbrock, M. M. Phillips, A. T. Koski, and R. Cohen for help in data acquisition and analysis and for interesting discussions. This research was partially supported by the NSF under grant AST 76-18440.

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