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THE LINE CONTINUUM LUMINOSITY RATIO IN AGN: OR ON THE "BALDWIN EFFECT"

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ABSTRACT

The luminosity dependence of the equivalent width of CIV in active galaxies, the "Baldwin" effect, is shown to be a consequence of a luminosity dependent ionization parameter, U. The available data, combined with a "standard" photoionization model yield $U \propto L^{-.25}$. This law also agrees with the lack of a "Baldwin" effect in Lyα or other hydrogen lines. A fit to the available data gives a weak indication that the mean covering factor decreases with increasing luminosity, consistent with the inference from X-ray observations.

We discuss, in the appendices, the effects of continuum shape and density on various line ratios of interest.

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I. INTRODUCTION

Observations of both high and low redshift quasars (Baldwin 1977; Baldwin et al. 1978) and Seyfert I galaxies (Wu, Boggess and Gull 1983) have shown that the equivalent width of the CIVλ1549 line in these objects is lower for higher luminosity objects, the so called "Baldwin effect". Such a correlation is important because it offers an empirical method of determining the intrinsic luminosities and distances of quasars (Baldwin et al. 1978) and may serve as a probe of the environment near the poorly understood central engine. Such an effect does not seem to be present in Lyα although it may be present in MgIIλ2798 (Baldwin et al. 1978). The reality of this "Baldwin" effect for radio quiet quasars has been questioned by Osmer (1980), even though it seems well established for radio loud objects.

We wish to show in this paper that the Baldwin effect in radio loud active galaxies can be understood primarily as a systematic decrease in ionization parameter with luminosity and secondarily perhaps a decrease of covering factor with luminosity (although these correlations may not be the only "cause" of the "Baldwin effect"). Previous interpretations have centered on the effects of inbedded dust (see Shuder and MacAlpine 1979).

II. MODEL

We use the photoionization code of Ferland (1981) in the manner described by Ferland and Mushotzky (1982). To calculate our models we have used solar abundances and an ionizing input spectrum of the form

$$\frac{dN}{dE} = A\, E^{-\alpha_1} \exp -(E/E_0) + B\, E^{-\alpha_2} \ \text{ph/cm}^2\ \text{sec eV}$$

α_1 = 2.2 (Malkan and Sargent 1982)

α_2 = 1.7 (Mushotzky 1982)

with A/B ~ 3 x 10^2. This reproduces the mean spectrum of Seyfert I's quite well (Wu, Boggess and Gull 1983), and corresponds to a α_{ox} of ~ 1.5, the mean value for X-ray detected optically selected AGN. We have chosen a cutoff value E_0 = 200 eV so as not to exceed the observed soft X-ray flux (see Appendix A). The code uses methods and assumptions very similar to those described by Kwan and Krolik (1981) (see also Davidson and Netzer 1979). We will be primarily interested in lines formed in the highly ionized H^+ zone of the broad line clouds, where the physical conditions are less sensitive to the exact details of the model such as line trapping or X-ray effects which may strongly effect such lines as Hα, Hβ or MgII. As a consequence our theoretical results are basically similar to those found by Davidson (1977), Shuder and MacAlpine (1979) and Weisheit, Shields and Tarter (1981).

High luminosity quasars apparently have a lower X-ray to optical ratio by a factor of ~ 50 (Reichert et al. 1982) than Seyfert galaxies such that A/B can be as large as 1.5 x 10^4. However we find that the conclusions we reach about Lyα, CIII] and CIV are relatively independent of the optical to X-ray ratio because these lines do not come from the "X-ray" heated deep zone (see Appendix A), however we do not examine the effect of possible variation in the UV index α, on line ratios. Because certain high ionization lines like O VI and NV and "low ionization" lines like MgII and Hβ are more sensitive to the ratio of optical to X-ray luminosity, L_O/L_X, one still should be careful in defining the continuum form. We have chosen models with constant density between log ρ = 9.5 and log ρ = 10.2 cm^{-3} and clouds with fixed column density N_H. The assumption of constant density rather than constant pressure seems as reasonable when it is realized that the sound crossing time for typical clouds (δr ~ 10^{13} cm, τ ~ 1 year) is of the order of the timescale for continuum variability. Therefore since the clouds are in virtually instantaneous thermal and ionization equilibrium they cannot be in pressure equilibriuim. In our models as long as log N_H is > 22.4 at/cm^2, and log U < -1.0, the CIII], Lyα and CIV line fluxes are almost independent of how thick the cloud is at these densities and ionization parameters. In most of our model runs CIII] was saturated by a column density of log $N_H \sim 22.4$, while Lyα and CIV were saturated at lower N_H.

The model assumes that there is only one "slab" at a given distance from the central source, and spherical symmetry in the broad line region (see Davidson 1977). We use the same definition of ionization parameter U as in Ferland and Mushotzky (1982); $U = Q(H)/4\pi\ r^2 c n_e$ where Q(H) is the number of ionizing photons per second and thus U depends on the continuum shape where log U is typical of the order of -2 for active galactic nuclei (Davidson and Netzer 1979).

III. RESULTS

As is shown in Figure 1, at a fixed continuum luminosity, the CIII], Lyα and CIV luminosities are a strong function of the density and ionization parameters. This has long been well known (see review by Davidson and Netzer 1979). Wu, Boggess and Gull (1983) point out that several objects with high CIII]/CIV ratios have high Lyα/CIV and that several others which have low CIII]/CIV have low Lyα/CIV. We wish to point out here that this correlation is very general. In Figure 2 we plot the ratio of CIII]/CIV vs Lyα/CIV for all the AGN in the literature we know of. On this graph we also draw lines of constant log ρ but varying ionization parameter, log U, from our model calculations. Note that because of the strong thermostat effect of these cooling lines, their strength is not strongly sensitive to the carbon abundance assumed (cf. Shuder and Mac Alpine 1979). Virtually all of the points in this diagram lie between the lines log ρ = 10 and log ρ = 9.5.

Assuming that this represents "correct" physics we can restrict ourselves to the majority of points that cluster on the log ρ = 9.5 line. We can then assign an effective ionization parameter log U_{eff}, for a given object appropriate for Lyα,CIII] and CIV, from the location of the object in Figure 2. We have chosen those objects that cluster with ±10% of the theoretical line, consistent with an estimate of observational errors. The many fewer points that appear to cluster around the other two lines do not allow a good estimate of the dependence of log U_{eff} on L to be determined.

We show in Figure 3 for Seyfert galaxies and QSO's a plot of log U_{eff} vs log L_{1450}, the luminosity of the source at 1450 Å . This latter value may be taken as indicative of the total luminosity of the source as measured by Baldwin and thus is appropriate for the Baldwin relation. It is quite clear from this plot that log U_{eff} is inversely related to Log L_{1450}. This relation has a linear regression coefficient R = .90 and is thus significant at greater than the 99.999% confidence level. The best fit power law gives log U ≈ -.25 log L_{1450}. The shall size of the exponent requires a large total range in L to see (which is why this effect was not noticed in samples restricted to high luminosity high redshift QSO's) but we feel it is quite significant.

It is interesting to note that comparison of the mean of CIII]/CIV and Lyα/CIV ratios for quasars and Seyferts separately, which has a much larger number of objects, also shows the same effect. The mean of Lyα/CIV for high z QSO's from Osmer (1980) and Osmer and Smith (1981) is ~ 2.5 while for Seyferts I's, of considerably lower luminosity, the ratio is 1.5 (Wu, Boggess and Gull). For CIII]/CIV the mean ratio for QSO's is .5 while for Seyferts it is .2. Since the "mean" luminosity at 1450 Å for the Osmer and Smith QSO's is log L_{1450} ~ 31.5 while for the Wu et al. sample it is log L_{1450} ~ 29.0, this also indicates in our representation of the data a luminosity dependent ionization parameter. One must of course also remember that the CIII]/CIV ratio is density sensitive and that some fraction of the observed variation could easily be due to variation in density from object to object (see Appendix B). However Lyα/CIV has only a very weak density dependence (for log U = -1.5, Lyα/CIV ~ $\rho^{+.07}$, 9.0 < log ρ < 10.2 from our calculations) so that most of the Lyα/CIV variation cannot be due to density effects alone. Similarily it is well established that the Lyα/CIV and CIII]/CIV ratios are independent of the X-ray to optical ratio (Kwan and Krolik 1981) (see Appendix A) (which is itself also a function of absolute luminosity (Zamorani 1982)). We therefore argue, tentatively, that a major fraction of the observed variation in the Lyα/CIV vs CIII]/CIV plane is due to variation in ionization parameter and that this variation is luminosity dependent. A similar suggestion for the origin of the CIII]/CIV ratio being lower for Seyfert I's than quasars was made by Wu, Boggess and Gull (1983).

IV. DISCUSSION

A. Baldwin Effect

Can this observed luminosity dependent ionization parameter account for the Baldwin effect? Roughly speaking, the luminosity in a given line is $L_{Line} = (\Omega/4\pi)\ A_L f_L(U)\ L_{cont.}$ In this expression L_{cont} is the luminosity in the continuum integrated over the frequency range appropriate to ionize the ion emitting the given line, $f_L(U)$ for several lines is shown in Figure 1 and A_L is a constant for a given line. In the following discussion the covering fraction, $\Omega/4\pi$, which is the fraction of central continuum photons intercepted by broad line clouds, is set equal to unity. For CIV we have, for log U < -2.5 (Figure 1) that $f_L(U) \sim U^{7/4}$ while for -2.5 < logU <- 1.5, $f_L(U) \sim U^{2/5}$. Thus since $U \sim L_{1450}^{-1/4}$ if we associate L_{cont} with L_{1450} one gets

$L_{CIV} \sim L_{1450}^{9/16}$ for log U_{eff} < -2.5 and $L_{CIV} \sim L_{1450}^{0.9}$ for -2.5 < log U_{eff} < -1.5. Using our calibration in Figure 3 of log L_{1450} vs Log U_{eff} we see that log $U_{eff} \sim -2.5$ is achieved at log $L_{1450} \sim 31.0$. This value of log L_{1450} is appropriate for Baldwin's (Baldwin 1977, Baldwin et al. 1978) sample of high redshift quasars. These authors find that $L_{CIV} \sim L_{1450}^{.33\pm.17}$ compared to our prediction of an index of .56 (the recent analysis of Kiang, Cheng and Zhou (1983) of Osmer's data gives gives $L_{CIV} \alpha L_{cont}^{.33\pm.1}$ for radio quiet objects). We consider this a reasonable agreement. Of course this requires that L_{cont} be linearly related to L_{1450}. A possible luminosity dependent covering fraction, such as has been observed in the X-ray band could make the agreement almost exact (see discussion in Section C.) More data points are necessary to define the log U vs Log L relation more clearly (Baldwin 1977, Baldwin et al. 1978).

Examination of Figure 6 of Wu, Boggess and Gull or Figure 6 of Wampler et al. (1983) shows that the Baldwin relation starts to fail badly at log $L_{1450} \sim 29\text{-}29.5$ ($M_{1550} = -22$) or in our transformed units, cf. Figure 3, log $U_{eff} \sim -1.75$ more or less where $f_L(U)$ for CIV flattens (Figure 1). That is, we <u>predict</u> that the Baldwin effect should become much weaker for lower luminosity AGN. This occurs when $f_L(U) \alpha U^{2/5}$ that is for Log L_{1450} < 30. At even higher values of U and, thus lower values of L, $f_L(U)$ is flat for CIV e.g. $L_{CIV} \alpha U^0$ and thus there should be <u>no</u> ionization parameter "Baldwin effect" consistent with the recent results of Wampler et al. (1983).

We thus feel that we can account for both the slope of the "Baldwin" relation and the place where it ceases to be significant from the L_{1450} vs. U relation. The lack of a "Baldwin" effect in Lyα, e.g. the fact that the luminosity in Lyα is linearly related to the continuum flux, is easily understood as well. Figure 1 shows that $L_{Ly_\alpha} \sim U^{-.25}$. Thus we predict that $L_{Ly\alpha} \sim L_{cont}^{1.06}$ consistent with Osmer's (1980) results.

B. Other Lines

What are the other predictions of such a model? As Kwan and Krolik (1981) point out, the high ionization lines such as OVI λ1035 and NV λ1240 are quite sensitive to log U variations. Our model would predict that low luminosity objects would have considerably stronger OVI and NV lines than high redshift quasars. Unfortunately there is very little data on NV from Seyferts and none on OVI.

If this idea is correct one might also see the "Baldwin effect" in an individual variable object, or if it had the proper ionization parameter perhaps even an "anti-Baldwin effect". An anti-Baldwin effect is predicted for objects with a low luminosity since for large U, log U > -1.5, $f(U) \propto U^{-.5}$. In fact, in NGC 4151, from the May 1978 to Oct 1978 IUE observations (Penston et al. 1981) show that the continuum at 2500 A decreased by 22% but that the flux in CIV did not change. On timescales much longer than the light travel time across the broad line region (.1 - 1 year) reverberation effects such as those discussed by Bahcall and Kozlovsky (1969) and Blandford and McKee (1982) are suppressed. Similarly in NGC 3783 (Barr, Willis and Wilson 1983) which has variability on a time scale of a month, longer than the light travel time across the broad line region in the object, it has been reported that a Baldwin type relation holds. Fitting the Barr et al. data we find $L_{CIV} \propto L_{1450}^{.25}$. If in this object $U \propto L_{cont}$ (we assume that the cloud position does not change), this gives using, Figure 1, a log $U_{eff} \sim -1.75$. Matching the variations in the Lyα/CIV vs CIII]/CIV plane by using Figure 2 for this object also give log $U_{eff} \sim -1.75$. For a luminosity of log $L_{1450} \approx 27.0$ this value of Log U is in general agreement with the overall log L_{1450} vs. log U_{eff} relation (Figure 3). Thus in this one object we get similar estimates for U from variations in line ratios, from its position in the continuum luminosity versus U plane and from the relationship between CIV and continuum luminosity.

We therefore conclude that much of the available data are consistent with the "Baldwin effect" both in the ensemble of active galaxies and in NGC 3783 being due primarily to luminosity related variations in the effective ionization parameters.

C. X-Ray Data and Covering Factor

It has been claimed (Holt et al. 1980; Mushotzky 1982; Lawrence and Elvis 1982) that the effective X-ray column density is related inversely to the X-ray luminosity L_X. If we assume that this is a covering factor effect one might expect to see it in the Lyα and CIV line fluxes, that is, since the higher luminosity objects have a lower covering factor, this would tend to depress the Lyα and CIV line fluxes systematically with luminosity. Inspection of Figure 6 of Wu, Boggess and Gull shows that for log L < 29.0 (where we predict that the ionization parameter dependent Baldwin effect should be weak or not present) that Log $L_{CIV} \propto L_{cont}^{.8}$, at roughly 3σ confidence, behaving as if the covering factor Ω was weakly dependent on L, e.g. $\Omega \propto L^{-.2}$. This small an effect would not be seen over a large dynamic range in L in the Lyα or CIV line fluxes since it would be dominated by the "Baldwin effect" at large L. This variation in covering factor infered from the CIV line predicts that, in the X-ray energy range, one would see the mean covering factor change from a (postulated) value of 1 at $L_X \sim 42.5$ (for NGC 4151) to .6 at $L_X \sim 43.5$ which would totally account for the observed X-ray absorption effect seen by Mushotzky (1982). That is, the fact that high luminosity active galaxies do not, typically, show X-ray absorption can be explained by a reduction in the mean covering fraction from 1 for low luminosity objects like NGC 4151 to ~ .7 for objects of a factor 10 higher X-ray luminosity.

If we include this luminosity dependent covering factor in our predictions, the slope of the best fit relation between CIV line flux and continuum luminosity changes from $L_{CIV} \propto L_{cont}^{+.56}$ to $L_{CIV} \propto L_{cont}^{+.36}$, in nearly perfect agreement with that measured by Baldwin and co-workers. We thus feel that all these results are compatible. It is interesting to note that if we extend this fit to the quasars of Log $L_X \sim 46$ we would predict a covering factor of .2, which is similar to that inferred for these objects by the Lyman continuum absorption arguments (Osmer 1980).

D. Can the Baldwin Effect be Seen In the Balmer Lines?

Inspection of Figure 3 shows that the other hydrogen lines (Hα, Hβ) show similar weak dependences on log U_{eff}. In particular, to compare with the data of Yee (1980) and Shuder (1981) we find that, roughly log $L_{H\alpha} \sim -.4$ log U, for Log U in the range -1.5 to -2.5 and log $L_{H\beta} \sim -.2$ log U for log U < -2.25. Thus we would predict log $L_{H\alpha} \sim 1.1$ log L_{cont} and log $L_{(H\beta)} \sim 1.05$ log L_{cont}. The actual fit Yee gives for quasars is log (L (Hβ)) ~ 1.00 log L_{cont} and Shuder gives log (L(Hα) ~ 1.05 log L_{cont}. The agreement between theory and observation again seems quite good. We have not taken possible systematic variations in covering factor (sec c) into account here.

V. CONCLUSIONS

We have established that there exists a luminosity-ionization parameter correlation for active galactic nuclei (Quasars and Seyfert I's). This correlation combined with photoionization model calculations predicts that the luminosity in CIV λ1549 should be proportional to the continuum luminosity to the 1/2 power at high luminosity, e.g., the Baldwin effect. At low luminosity the effect should get weaker and disappear for low luminosity AGN's.

We can further show that such an effect should be present in individual galaxies when their luminosity changes, as has been seen by Barr, Willis and Wilson (1983) for NGC 3783.

In addition the calculations show that there should not exist a Baldwin effect in Lyα, Hα, and Hβ . Observationally this has been shown by Yee (1980), Shuder (1981) and others.

The lack of a Baldwin relation at low luminosity allows us to investigate the covering factor, $\Omega/4\pi$, vs luminosity relation in low luminosity AGN. We find that, $\Omega \propto L^{-.2}$. This weak anti-correlation is important enough to account for both the observed anti-correlation seen in the X-ray between luminosity and X-ray absorption as well as to predict the low covering fractions observed in high luminosity QSO's.

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FIGURE CAPTIONS

Figure 1 - Relative line fluxes, $f_L(U)$, for Lyα, CIV CIII] (1909λ), MgII(2798), Hα, Hβ and HeII(4686) vs. the ionization parameter log U at a fixed density (log ρ = 10.0) and fixed column density log N_H = 22.8 at/cm^2 for the continuum specified in the text

Figure 2 - Log CIII]/CIV vs log Lyα/CIV for a sample of active galaxies. The lines are theoretical line ratio's from photoionization models. The tic marks are at log U_{eff} = -1, -1.5, -2.0, -2.5, -2.75 for log ρ = 9.5, log U_{eff} = -1.5, -2.0, -2.5, -2.75 and -3.0 for log ρ = 10.0 and at log U_{eff} = -1.5, -2.0, -2.5, -2.75 and -3.25 for log ρ 10.2. The data marked by an open symbol are from IUE (Wu, Boggess and Gull 1983), Green et al. 1980; Ulrich and Boisson 1983; and Malkan 1983). The solid dots are from Baldwin and Netzer (1978), the solid diamonds from Oke and Korycansky (1982). The open square is the "mean value" for Osmers quasars and the star the mean value for Seyferts.

Figure 3 - Log luminosity at 1450 Å vs log U_{eff}. The data are drawn from Figure 2 from the points that cluster along the log ρ = 9.5 line. Symbols have same meaning as in Figure 2. The line is the best fit power law to the data of slope -.25. The Oke and Korycansky points have been converted to 1450 Å continuua following Wampler et al. (1983). Not all points in Figure 2 have continuum L_{1450} available in the literature and so do not appear in Figure 3.

TABLE 1. LINE RATIOS FOR MODELS 1-5

log U = -3.0

	Model 1	2	3	4	5
Lyα/CIV	23.4	22.8	23.9	24.8	28.5
CIII]/CIV	1.86	2.05	2.16	2.13	2.0
Hα/Hβ	17.3	13.1	12.1	15.5	18.7
MgII/Hβ	21.6	13.1	11.1	18.4	2.47

log U = -2.0

	Model 1	2	3	4	5
Lyα/CIV	1.48	1.33	1.42	1.27	1.13
CIII]/CIV	.18	.155	.16	.15	.13
Hα/Hβ	3.9	4.1	5.52	4.2	3.5
MgII/Hβ	2.9	1.76	2.00	3.03	1.7

log U = -1.00

	Model 1	2	3	4	5
Lyα/CIV	1.04	1.67	1.92	1.32	.90
CIII]/CIV	.08	.12	.13	.103	.08
Hα/Hβ	1.41	1.36	1.33	1.35	1.68
MgII/Hβ	.58	.316	.22	.415	.32

APPENDIX A: CONTINUUM EFFECTS

In this appendix we will consider the effects of varying the continuum form on the strong emission lines, Lyα, Hα, Hβ, CIII], CIV and MgII. We caution the reader that since Hα, Hβ and MgII are generated mostly in the thick cool regions of the cloud whose physics is not yet totally understood that these results are primarily illustrative. We have constant density clouds of thickness $\log N_H = 22.8$ and density $\log \rho = 10.0$. We pick 4 model spectra of the form $F_\nu = A\text{-}\nu^{-\alpha_1} \exp/-(E)/E_0) + B\nu^{-\alpha_2}$ ph/cm^2 sec eV with $\alpha_2 = 1.7$, $\alpha_1 = 2.2$ and vary E_0 and A/B.

Model 1 has A/B = 300, which corresponds to $\alpha_{ox} = 1.51$ with $E_0 = \infty$.

Model 2 has E_0 = 200 eV and A/B = 300.

Model 3 has E_0 = 200 eV A/B = 7200 which corresponds to $\alpha_{ox} = 2.05$.

Model 4 has E_0 = 200 eV A/B = 2.3 or $\alpha_{ox} = 1.28$

Model 5 has $E_0 \doteq 200$, A/B = .4, $\alpha_{ox} = 1.00$

This range of α_{ox} from 1.00 to 2.05 covers, roughly, the complete range of α_{ox} as seen by Zamorani et al. (1981). A quick inspection of Table I shows that the line ratios are almost invariant with respect to the models. That is, within the limited range of continuum models we have chosen, the line ratios are almost invariant with respect to the exact form of the soft X-ray (.2-5 keV) spectrum or to the optical/X-ray ratio. The largest changes between models is seen between models 3 and 4 the $\alpha_{ox} = 2.05$ and 1.28 models. Model 4 has a systematically higher ratio of MgII/Hβ. Our models are consistent with the observational results of Kriss (1982) on the Lyα/CIV ratio showing only a weak anti-correlation with α_{ox}.

At higher values of L_X/L_O e.g. α_{ox} =1.0, Model 5, the log ρ = 10.0, log N_H = 22.8 clouds become more ionized all the way through and the nature of the models change since there is no longer a very cool "vasty deep". This strongly affects the MgII, and H_β lines.

APPENDIX B: DENSITY EFFECTS

The referee has also suggested that we should clarify the use of CIII] as both a density and ionization parameter diagnostic. In this section we consider the CIII]/CIV ratio for a constant continuum and column density but variable density and ionization parameter. In Table 2 of Appendix II we show our results for a model with A/B = 7200 (e.g. low X-ray flux α_{OX} =2.05), and no cutoff and constant thickness log N_H = 22.8 for 3 different densities and ionization parameters.

Table 2

CIII]/CIV Ratio

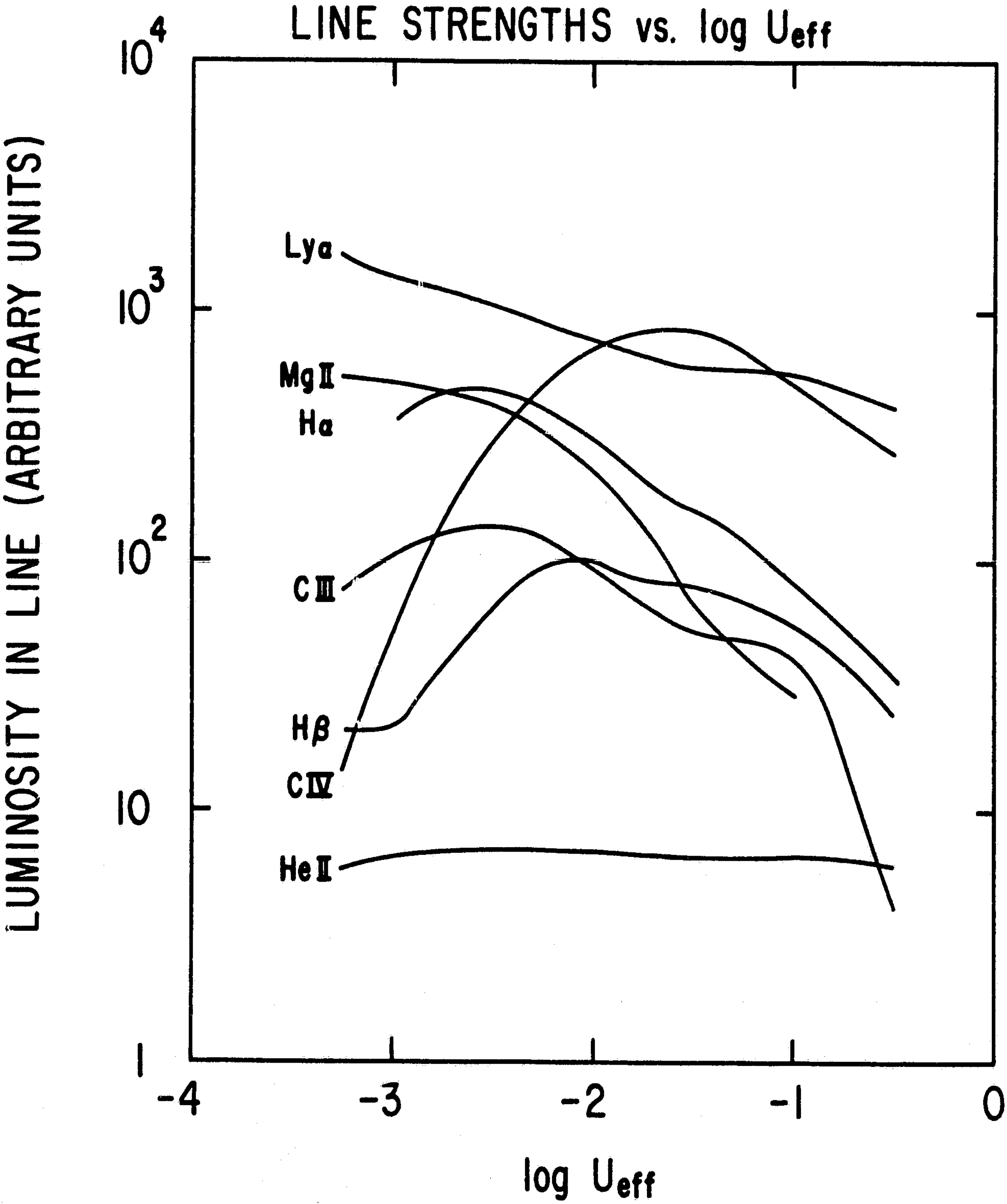
	log ρ		
log U	9.5	10.0	10.2
-2.50	.817	.420	.289
-2.00	.27	.129	.093
-1.50	.092	.060	.053

As is easily seen the results are degenerate. One can get the same values of CIII]/CIV for all 3 densities and ionization paramters. Thus one cannot use only the CIII]/CIV ratio to determine density or ionization parameter. However as Figure 2 and Table 3 show, for a given continuum Lyα/CIV is sensitive almost totally to ionization parameter and not density.

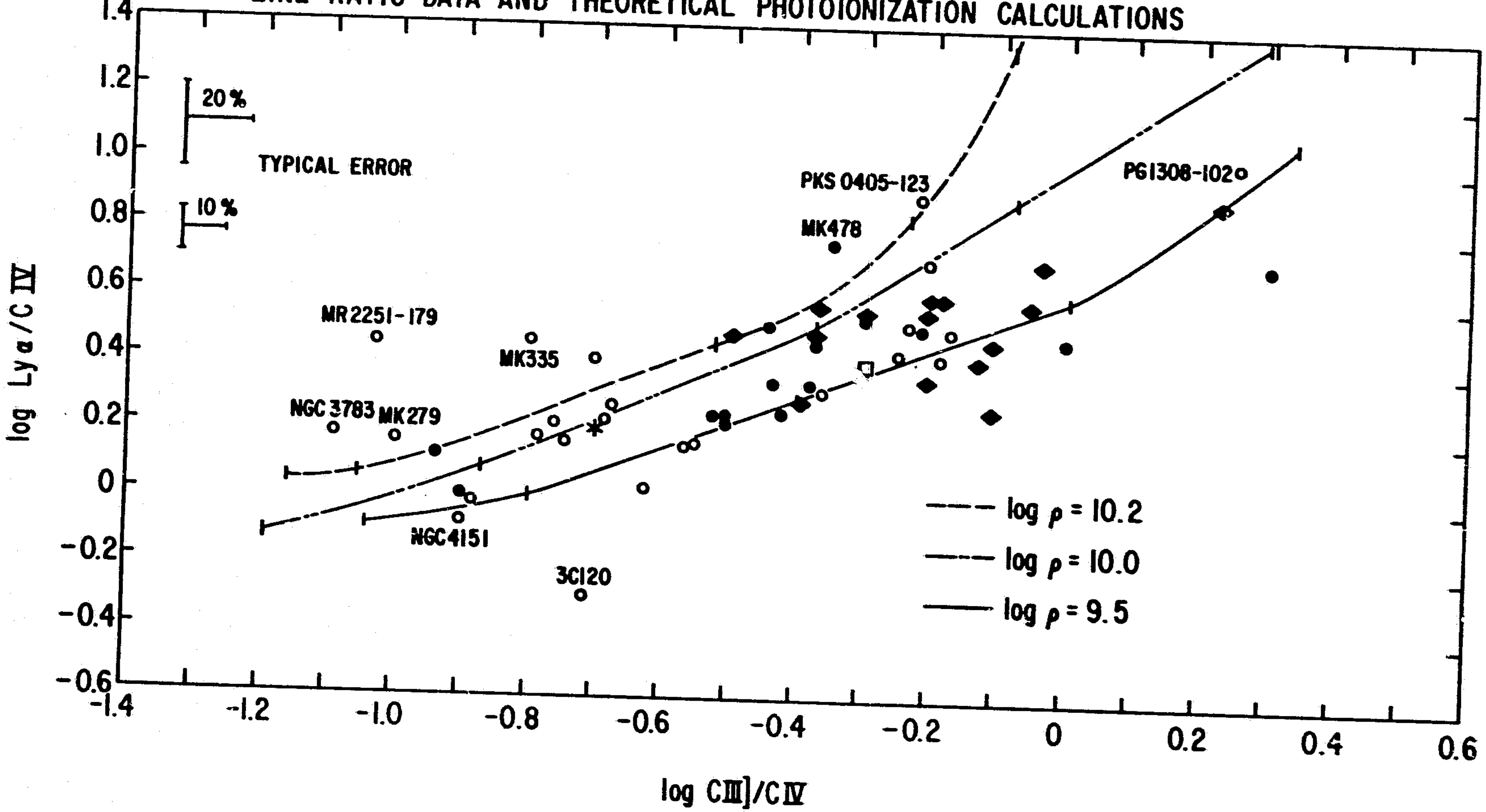
TABLE 3: Lyα/CIV Ratio as a Function of Density and log U

	log ρ		
log U	9.5	10.0	10.2
-2.50	3.88	3.28	2.85
-2.00	1.26	1.08	.94
-1.50	.784	.755	.71

Thus over fairly wide ranges in density and ionization parameter one can estimate both log U and log ρ by using the two line ratios Lyα/CIV and CIII]/CIV if the measurements have accuracies of better than 10%.


LINE STRENGTHS vs. log Ueff
LUMINOSITY IN LINE (ARBITRARY UNITS)
10^4
10^3
10^2
10
1
Lyα
Mg II
Hα
C III
Hβ
C IV
He II
-4
-3
-2
-1
0
log Ueff

LINE RATIO DATA AND THEORETICAL PHOTOIONIZATION CALCULATIONS



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log L_{1450}, log U_{eff} RELATION