An Atlas of Computed Equivalent Widths of Quasar Broad Emission Lines

Kirk Korista  
*University of Kentucky*

Jack Baldwin  
*Cerro Tololo Inter-American Observatory, Chile*

Gary J. Ferland  
*University of Kentucky, gary@uky.edu*

Dima Verner  
*University of Kentucky*

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AN ATLAS OF COMPUTED EQUIVALENT WIDTHS OF QUASAR BROAD EMISSION LINES

KIRK KORISTA
Department of Physics & Astronomy, University of Kentucky, Lexington, KY 40506

JACK BALDWIN
Cerro Tololo Inter-American Observatory,1 Casilla 603, La Serena, Chile

AND

GARY FERLAND AND DIMA VERNER
Department of Physics and Astronomy, University of Kentucky, Lexington, KY 40506

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ABSTRACT

We present graphically the results of several thousand photoionization calculations of broad emission-line clouds in quasars, spanning 7 orders of magnitude in hydrogen ionizing flux and particle density. The equivalent widths of 42 quasar emission lines are presented as contours in the particle density–ionizing flux plane for a typical incident continuum shape, solar chemical abundances, and cloud column density of \( \text{N(H)} = 10^{23} \text{ cm}^{-2} \). Results are similarly given for a small subset of emission lines for two other column densities (\( 10^{22} \text{ cm}^{-2} \) and \( 10^{24} \text{ cm}^{-2} \)), five other incident continuum shapes, and a gas metallicity of 5 \( Z_\odot \). These graphs should prove useful in the analysis of quasar emission-line data and in the detailed modeling of quasar broad emission-line regions. The digital results of these emission-line grids and many more are available over the Internet.

Subject headings: atlases — quasars: emission lines

1. INTRODUCTION

Early photoionization calculations could roughly reproduce the average observed quasar broad emission-line (BEL) spectrum in a single “cloud,” i.e., one with a single column density \( \text{[N(H)] } \sim 10^{23} \text{ cm}^{-2} \), gas density \( \sim 10^{10} \text{ cm}^{-3} \), and ionization parameter \( \langle U \rangle \equiv n_{\text{pH}}/n_e \sim 0.01 \) (Davidson 1977; Davidson & Netzer 1979; Kwan & Krolik 1981). However, in the past decade, spectroscopic observations have pointed to the presence of a wide distribution in the emission-line cloud properties within each quasar (Gaskell 1982; Wilkes 1984; Espey et al. 1989; Corbin 1989; Clavel et al. 1991; Peterson 1993), prompting the more recent multiclouid, single pressure law calculations by Rees, Netzer, & Ferland (1989), Krolik et al. (1991), Goad, O’Brien, & Gondhalekar (1993), and O’Brien, Goad, & Gondhalekar (1994, 1995). Most recently, Baldwin et al. (1995) found that simply integrating the emission from a wide distribution in cloud gas properties (gas density, ionizing flux, and column density) results in a spectrum that is consistent with composite quasar spectra and may offer simple solutions to some observational problems (e.g., emission-line profile differences and reverberation). This hypothesis will be further investigated in future papers (Korista et al. 1997).

In anticipation of future, more advanced modeling of the broad emission-line regions (BLRs) of quasars and active galactic nuclei (AGNs), we present here the results of thousands of photoionization calculations that span 7 orders of magnitude in hydrogen ionizing flux and particle density. The equivalent widths of 42 of the more prominent quasar emission lines are presented as contours in the particle density–ionizing flux plane, for a typical incident continuum shape, solar chemical abundances, and cloud column density of \( \text{N(H)} = 10^{23} \text{ cm}^{-2} \). Results are similarly given for a small subset of emission lines for two other column densities, five other incident continuum shapes, and a gas metallicity of 5 \( Z_\odot \). We present this as a foundation for future research, and also as an interpretational aid for the spectroscopic observer.

We describe the calculations and the emission-line equivalent width maps in § 2 and conclude in § 3. The digital results of these and many more BEL photoionization grids will be available in electronic form over the Internet. Instructions for electronic retrieval are also given in § 3.

2. THE PHOTOIONIZATION GRIDS

2.1. The Calculations

The line spectrum emitted by individual quasar “clouds” (whatever their nature) depends on a number of parameters, namely, the gas density, the gas column density, the flux and shape of the incident continuum, and the gas chemical abundances. The standard picture is that each observed line is the result of a superposition of line emission from a large number of clouds, each emitting at their thermal width (Davidson & Netzer 1979). The present calculations assume thermal velocity line widths in each cloud. The presence of significant turbulence or streaming motions within the emitting region would have significant effects on the results presented below and will be the subject of future work. These would mainly act to alter the line escape probabilities (perhaps along preferred directions), thereby reducing the effects of line thermalization at high density and optical depth, and continuum pumping contributions to some emission lines could also become significant.

After choosing a particular chemical abundance (initially solar), incident continuum shape, and cloud hydrogen column density (initially \( 10^{23} \text{ cm}^{-2} \)), we computed an
emission-line spectrum for each coordinate pair in the gas density–hydrogen-ionizing photon flux plane \([\log n(H), \log \Phi(H)]\) using the code CLOUDY, version 90.02d (Ferland 1996; Ferland et al. 1996). Constant hydrogen density throughout each cloud was assumed. The results tend to be similar for a similar ionization parameter, defined \(U(H) = \Phi(H)/n(H)c\); lines in the gas density–ionizing flux plane with 45° slopes will be of constant \(U(H)c\). With an origin of \(\log n(H) = 7, \log \Phi(H) = 17\), the grid was stepped in 0.25 dex increments, and spanned 7 orders of magnitude in each direction, for a total of 841 simulations per grid. This should more than cover the parameter space of the broad emission-line clouds. Gas simulations per grid. This should more than cover the parameter space of the broad emission-line clouds. Gas densities greater than \(10^{14} \text{cm}^{-3}\) were not considered, since in this regime the calculations are not deemed sufficiently accurate and such clouds are mainly continuum sources (Rees et al. 1989).

The chosen form of the incident continuum shape was a combination of a \(f_\lambda \propto \nu^{-0.5} \exp(-\nu/kT_{\text{out}})\) UV bump with an X-ray power law of the form \(f_\lambda \propto \nu^{-1}\) spanning 13.6 eV to 100 keV, appropriate for radio-quiet quasars and AGNs (Elvis et al. 1994). We considered two values of the UV bump cutoff temperature, \(T_{\text{out}}\), such that the energy in the UV bump peaked at \(E_{\text{peak}} \approx 22\) eV and 44 eV, corresponding to \(\log T_{\text{out}} = 5.7, 6.0\), respectively. The UV bump was also cut off in the infrared with a temperature \(kT_{\text{IR}} = 0.01\) ryd, corresponding to 9.1 \(\mu\)m. Most of the observed IR continuum is thought to originate in warm dust, far outside the BEL region (Sanders et al. 1989; Barvainis 1990, 1992). Free-free heating from a strong incident IR continuum would have profound effects on the ionization and thermal properties of high-density clouds (Ferland & Persson 1989; Ferland et al. 1992). The UV and X-ray continuum components were combined using a range of UV to X-ray logarithmic spectral slopes of \(\alpha_\text{ox} = -1.2, -1.4, -1.6\) (note that we prefer the convention \(f_\lambda \propto \nu^\alpha\)). It is defined

\[
\frac{f_{\lambda}(2 \text{ keV})}{f_{\lambda}(2500 \text{ A})} = 403.3^{\alpha_\text{ox}}.
\]

We plot the incident continua considered here in Figure 1.

For our baseline grid we chose the continuum that might typify an average QSO: \(E_{\text{peak}} = 44\) eV and \(\alpha_\text{ox} = -1.4\). For the hardest value of \(\alpha_\text{ox}\) considered here (\(\alpha_\text{ox} = -1.2\), generally applicable to Seyfert 1 type AGNs, the slope of the exponential portion of the UV bump has a value of roughly \(-2.3\), similar to observed slopes of soft X-ray excesses (e.g., Walter & Fink 1993).

2.2. The Baseline Grid

Our baseline grid assumes solar abundances, a cloud column density of \(10^{23} \text{cm}^{-2}\), and the baseline incident continuum described above. CLOUDY now considers the ionization balance of the first 30 elements; solar abundances are from Grevesse & Anders (1989) and Grevesse & Noels (1993).

\[
\begin{align*}
\text{H: } & 1.00E+00, \text{ He: } 1.00E-01, \text{ Li: } 2.04E-09, \text{ Be: } 2.63E-11, \text{ B: } 7.59E-10, \text{ C: } 3.55E-04, \text{ N: } 9.33E-05, \text{ O: } 7.41E-04, \text{ F: } 3.02E-08, \text{ Ne: } 1.17E-04, \text{ Na: } 2.06E-06, \\
\text{Mg: } & 3.80E-05, \text{ Al: } 2.95E-06, \text{ Si: } 3.55E-05, \text{ P: } 3.73E-07, \text{ S: } 1.62E-05, \text{ Cl: } 1.88E-07, \text{ Ar: } 3.98E-06, \text{ K: } 1.35E-07, \text{ Ca: } 2.29E-06, \text{ Sc: } 1.58E-09, \text{ Ti: } 1.10E-07, \text{ V: } 1.05E-08, \text{ Cr: } 4.84E-07, \text{ Mn: } 3.42E-07, \text{ Fe: } 3.24E-05, \\
\text{Co: } & 8.32E-08, \text{ Ni: } 1.76E-06, \text{ Cu: } 1.87E-08, \text{ Zn: } 4.52E-08.
\end{align*}
\]

2.2.1. The Electron Temperature at the Face of the Cloud

Here we illustrate the dependence of the cloud gas temperatures on its position in the gas density–ionizing flux plane. In Figure 2 we plot contours of equal electron temperature at the face \(T_{\text{face}}\) of the cloud in this plane, assuming solar chemical abundances and the baseline incident continuum \(E_{\text{peak}} = 44\) eV and \(\alpha_\text{ox} = -1.4\). Both parameters will affect the details of this plot, but the trends

![Figure 1](image1.png)

**Fig. 1.**—Continuum spectral energy distributions considered in this paper. The UV bump peaks at \(E_{\text{peak}} \approx 44\) eV for the solid lines and at \(E_{\text{peak}} \approx 22\) eV for the dashed lines. Three separate values of \(\alpha_\text{ox}\) were considered, top to bottom: \(-1.2, -1.4, -1.6\). All continua plotted here have the same flux in hydrogen ionizing photons.

![Figure 2](image2.png)

**Fig. 2.**—Contours of constant logarithm of the electron temperature at the front face (first zone) of the cloud as a function of hydrogen ionizing photon flux and hydrogen density. The baseline incident continuum (a UV bump that peaks near 44 eV and an \(\alpha_\text{ox} = -1.40\)) and solar chemical abundances were assumed. The contours of 10⁸ K and 10⁹ K are both labeled and increase monotonically from the lower right corner to the upper left, where the Compton temperature for this continuum is reached \((4.7 \times 10^9\) K). The solid contours are decades, and the dotted contours are 0.1 dex increments.
Collisionally excited lines such as C IV $\lambda 1549$ (Fig. 3d) generally show a band of efficient reprocessing running at constant $U(H) \equiv \Phi(H)/n(H)c$ along the center of a diagonal ridge from high $\Phi(H)$ and $n(H)$ to low $\Phi(H)$ and $n(H)$. For C IV $\lambda 1549$ this ridge corresponds to a log $U(H) \sim -1.5$. The gentle decrease in $W_j$ along the ridge at constant $U(H)$ is the result of thermalization, described further below. The $W_j$ decreases sharply when moving orthogonal to the ridge because $U(H)$ is either too low (lower right) or too high (upper left) to produce the line efficiently. For a column density of $10^{23}$ cm$^{-2}$, clouds with log $U(H) \gtrsim 0.5$ are optically thin to He$^+$ ionizing photons ($h\nu \gtrsim 54$ eV) and so reprocess little of the incident continuum. C IV $\lambda 1549$ can be contrasted with a lower ionization line such as C III $\lambda 977$ (Fig. 3b), whose peak $W_j$ is shifted to lower log $U(H)$ ($\approx -2.25$), or to the high ionization O VI $\lambda 1034$ (Fig. 3b), shifted to higher log $U(H)$ ($\approx 0$).

A few effects modify the ridge of peak emission efficiency. The high ionization potential, high excitation energy of the Ne VIII $\lambda 774$ emission line along with the finite cloud column density together conspire to make its ridge of reprocessing efficiency very narrow in Figure 3a. The required ionization parameter is large, log $U(H) > 0.5$, and clouds with column densities of $10^{23}$ cm$^{-2}$ are becoming optically thin to He$^+$ ionizing photons; this line is nearly fully formed within such clouds (see Hamann et al. 1995). However, to fully form the peak ridge in the $W_j$ distribution of Ne VIII $\lambda 774$ in the density–ionizing flux plane requires larger column densities and ionization parameters [log $N(H) \sim 10^{24}$ cm$^{-2}$, log $U(H) \sim 1$]. Because of their narrowness, the $W_j$(Ne VIII) contours are best viewed by looking obliquely along the diagonal ridge. This effect will also be important to Mg x $\lambda 615$, and to a lesser degree O VI $\lambda 1034$, at this cloud column density.

The second effect is thermalization. This is most readily seen when comparing an intercombination line with a resonance line of the same ion. The classic example is C III $\lambda 977$ and C IV $\lambda 1549$ (Figs. 3b and 3e). While their ridges of peak $W_j$ have nearly the same ionization parameter [log $U(H) \approx -2.5$], the intercombination line begins to thermalize at densities $\lesssim 10^9$ cm$^{-3}$, while the resonance line does not begin to thermalize until the density has reached $\gtrsim 10^{12}$ cm$^{-3}$. A smaller gas density at the same $U(H)$ means smaller ionizing fluxes, corresponding to larger distances from an isotropically emitting continuum source. These two lines may be emitted in very different clouds. Thermalization at large optical depth is the reason for the peculiar $W_j$ distributions in lines such as O i $\lambda 1304$ and Mg ii $\lambda 2798$ (Figs. 3c and 3f). The O i line is also extremely sensitive to the presence of the hydrogen ionization front within the cloud; this accounts for the "noise" in the contours along its upper boundary. Emission lines that continue to become stronger at densities greater than $10^{11}$ cm$^{-3}$, as the traditional coolants become thermalized, are those that lie in the Lyman continuum, C III $\lambda 977$, C IV $\lambda 979$, C III* $\lambda 1176$, N VI, C IV $\lambda 1549$, Si IV $\lambda 1397$, Al III $\lambda 1859$, and Mg ii $\lambda 2798$. In the optical, Ca ii (H and K, and the near-IR triplet), and Na i $\lambda 5895$, become increasingly strong at very high densities. The strengths of these lines should be important indicators of the importance of ionized high-density clouds in the BLR.

One other effect is readily apparent in the $W_j$ distribu-

2.2.2. Emission-Line Equivalent Widths

In Figures 3a–3g we present contours of logarithmic equivalent width of 42 quasar emission lines in the log $n(H)$–log $\Phi(H)$ plane. The equivalent width ($W_j$ in Å) is measured relative to the incident continuum at 1216 Å for full source coverage, and is a measure of the cloud’s ability to reprocess the continuum into the emission line. Here, full source coverage means that the "sky," from the perspective of the continuum source, is completely covered by clouds: $f_c \equiv 1$. Results for cloud covering fractions less than 1 may be obtained through a simple rescaling. The $W_j$ distributions are laid out in order of increasing wavelength of the emission line, and the minimum contour plotted has a value of 1 Å in every case. Most of the first seven far-UV emission lines have rarely, if ever, been reported, and they are plotted in light of the recent Hubble Space Telescope spectra of $z \sim 1$ quasars. Baldwin et al. (1995) discussed some of the details of the $W_j$ distributions, and we elaborate on some of their discussion below.
Fig. 3—(a) Contours of \( \log W \) for six emission lines for the baseline grid are shown as a function of the hydrogen density and flux of hydrogen ionizing photons. The chemical abundances are solar, the cloud column density is \( 10^{23} \text{ cm}^{-2} \), the continuum spectral energy distribution has a UV bump that peaks near 44 eV and an \( x_o = -1.40 \). Line strengths are expressed as logarithmic equivalent widths referenced to the incident continuum at 1216 Å for full source coverage. In this and in all figures that follow, the smallest decade contoured is 1 Å, each solid line is 1 dex, and dotted lines represent 0.2 dex steps. In each case the peak in the equivalent width distribution lies beneath the center of a solid triangle. The contours generally decrease monotonically from the peak to the 1 Å contour. See text for further details. The solid star is a reference point marking the "standard BLR" parameters discussed by Davidson & Netzer (1979). (b) Same as (a) for other emission lines. (c) Same as (a) for other emission lines. (d) Same as (a) for other emission lines. (e) Same as (a) for other emission lines. (f) Same as (a) for other emission lines. (g) Same as (a) for other emission lines.
tions of those lines formed in the He$^+$ zone: in the gas density–ionizing flux plane a secondary, more localized ridge of high efficiency forms at larger $U(H)$ for gas densities \( \gtrsim 10^9 \text{ cm}^{-3} \). This effect is seen as secondary peaks in the $W_C(N \text{ m} \lambda 1750)$ and $W_C(C \text{ m} \lambda 1909)$ located near the coordinates (10.00, 19.75; Fig. 3e) and (9.50, 19.50; Fig. 3e), respectively, or as bulges in the $W_E$ distributions of $C \text{ ii} \lambda 1335, C \text{ iii} \lambda 977, N \text{ iii} \lambda 990, O \text{ iii} \lambda 1663$, and $Si \text{ iv} \lambda 1397$. For the relevant ionization parameters, an extended H$^+$–He$^+$ Strömgren zone forms in these clouds, increasing the relative emitting volumes for the aforementioned lines. This line emission eventually thermalizes at higher flux levels at constant $U(H)$ (i.e., for $\log n(H) \gtrsim 10^{10-11}$ cm$^{-3}$). This effect will be more important for higher column density clouds. Note that considerable overlap in the efficient emission of $C \text{ iii} \lambda 977$ and $C \text{ iii} \lambda 1909$ occurs for clouds whose properties lie in this region in the gas density–ionizing flux plane, in contrast to the ridge of primary efficiency at lower $U(H)$, as discussed above.

It should be noted by the reader that dielectronic recombination contributes significantly to the emission of several high-excitation lines, such as $C \text{ ii} \lambda 1335, C \text{ iii} \lambda 977, C \text{ iii}^* \lambda 1176, N \text{ iii} \lambda 990, N \text{ iv} \lambda 764, O \text{ iii} \lambda 835$, and $O \text{ v} \lambda 630$. This contribution tends to be more important for the lower ionization lines, because the collisional rates are small due to the Boltzmann factor. The recombination rates were taken from Nussbaumer & Storey (1983). The recombination contribution is also very important in the “bulge” and “secondary peak” regions in the gas density–ionizing flux plane for several of the lines that have these features, just described above. This is likely due to the fact that these lines at these positions in the gas density–ionizing flux plane are forming at larger depths in the cloud, where the temperatures are lower.
Finally, we do not investigate here the complicated emission from Fe II. The present version of CLOUDY predicts the heating and cooling contributions from Fe II based upon a modified version of the Wills, Netzer, & Wills (1985) model and will be discussed elsewhere (Hamann et al. 1997). More advanced calculations of the emission of Fe II and its role in the thermal balance of BEL clouds will be the subject of future work (see Verner et al. 1995).

2.2.4. The Hydrogen and Helium Lines

Lines of $H^0$, $He^0$, and $He^+$ are largely produced via recombination and emitted over a wider area on the gas density–ionizing flux plane, including the low $\Phi(H)$–high $n(H)$ regions. This is because these ions still exist under these conditions. At sufficiently high ionization parameter for the given cloud column density, the $H$, $He$, and $He^+$ ionization fronts reach the backs of the clouds causing the dramatic declines in $W_j$ of the Balmer lines, He I $\lambda5876$, and He II $\lambda4686$ (see Figs. 3f and 3g). These same lines have their peak efficiencies at high densities [$\log n(H) \geq 12$] but different ionizing photon fluxes. Note that in this high-density regime, substantial emission arises from collisional excitation. A feature common to most of the hydrogen and helium emission lines is saturation at high continuum fluxes. In contrast to the excited state transitions of $H$ and $He$, Ly$\alpha$ $\lambda1216$ thermalizes at high density as well as high flux (Fig. 3c; see also Ly$\beta$ and Ly$\gamma$ in Fig. 3b). Another common feature is that they weaken in the direction of very high density and very low flux (lower right corners) where either the ionized fractions of the $H$, $He$ ions are becoming very small or the temperature is becoming too low to support the collisional excitation of the neutrals. Note that the Balmer and Paschen continua "$W_j$" distributions (Figs. 3f and 3g) are the integrated fluxes from these diffuse continua ratioed to the incident continuum flux-density at 1216 $\AA$. Finally, we note that the assumed ionizing spectrum predicts a $W_\alpha(Ly\alpha) \approx 1089 \, \AA$ (3.04 in the logarithm) for full coverage by an optically thick cloud if all hydrogen ionizing photons are converted into Ly$\alpha$. Compare this with its computed $W_j$ contours in Figure 3c. Thermalization and destruction via background continuum opacities (Balmer continuum, Fe II, etc.) act to diminish this conversion efficiency (Davidson & Netzer 1979; Shields & Ferland 1993).

2.3. Other Cloud Column Densities

For solar abundances and the same incident continuum shape, Figures 4a–4c show the contours of $\log W_j$ for six selected emission lines for cloud column densities of $10^{22}$ cm$^{-2}$, $10^{23}$ cm$^{-2}$, and $10^{24}$ cm$^{-2}$, respectively. A comparison between the two extremes, Figures 4a and 4c, shows the expected results. For the hydrogen and helium recombination lines (left panels), the ionization parameter that fully ionizes the clouds is simply proportional to the cloud column density: $N(H^+)$ $\approx 10^{23.1} \times U(H)$ cm$^{-2}$.

This region of dramatic decline in $W_j$ also shifts to lower $U(H)$ with a decrease in the cloud column density for the collisionally excited metal lines (Fig. 4, right panels). The high-ionization lines, for example $O$ VI $\lambda1034$, are affected in an additional way: the position of the ridge top shifts to lower $U(H)$ for smaller column densities in order for a sufficient volume of $O^{+5}$ to exist within the cloud. The combined effects of these act to first diminish the lines’ ridge $W_j$ areas in the gas density–ionizing flux plane and eventually to reduce their peak contour values as the cloud column density is decreased. Thus, for a distribution in cloud column densities the highest emission lines are emitted most efficiently in the highest column density clouds. As an illustration of this we note that efficient emitters of $O$ VI $\lambda1034$ are mainly optically thick clouds whose column densities are $10^{24}$ cm$^{-2}$, a roughly even mixture of optically thick/thin clouds whose column densities are $10^{23}$ cm$^{-2}$, and mainly optically thin clouds whose column densities are $10^{22}$ cm$^{-2}$. This can be seen by comparing the ridge tops of this line for the three column densities to a line representing the ionization parameter at which the cloud becomes optically thin to hydrogen ionizing photons for that column density.

Finally, the $W_j$ distributions in the low-ionization lines, such as Mg II $\lambda2798$, primarily formed in a partially ionized hydrogen zone (PIZ), are not strongly affected at significant $W_j$ until the cloud column density drops substantially below $10^{22}$ cm$^{-2}$. This is also true of the hydrogen and helium emission lines at high density.

2.4. Other Ionizing Continuum Shapes

In Figures 5a–5e we show the $W_j$ distributions for the same six emission lines for solar abundances, a cloud column density of $10^{23}$ cm$^{-2}$, and five other incident continuum shapes (see Fig. 1). The results for the baseline continuum are shown in Figure 4b. Moving from the hardest (Fig. 5a) to the softest (Fig. 5e) continuum, the major change for most emission lines is that the value of the peak equivalent width diminishes, and/or the peak contours shrink in area in the gas density–ionizing flux plane. When comparing the results between the two types of UV bumps, about 0.15 dex of the changes in the peak line equivalent widths are due to the fact that for the same number of hydrogen ionizing photons, a softer UV bump will have more flux in the observed UV continuum upon which the lines lie than a harder one (see Fig. 1). The remaining differences are due to the quantity of photons at relevant energies to produce and excite the ions. Some line ratios, such as Ly$\alpha$/He II, are expected to be sensitive mainly to the hardness of the UV bump [$n_{ph}(912 \, \AA)/n_{ph}(228 \, \AA)$], while those involving the strong metal line coolants (e.g., Ly$\beta$/C IV and C IV/He II) should be dependent on both the hardness of the UV bump and $x_{\alpha}$. It is also the case for many of the metal lines that the upper boundary on $U(H)$ for significant reprocessing efficiency shifts to lower $U(H)$ for harder continua. This is because continua with larger ratios of soft X-ray to 912 $\AA$ photons are more efficient in stripping electrons from the ionized metals. This effect is especially apparent in lines like $O$ VI $\lambda1034$ (compare Figs. 5a and 5e). Note, however, that the contours of lines formed in a PIZ, like Mg II $\lambda2798$, become larger in the directions of larger $U(H)$ for harder continua, because the volume of a PIZ within a cloud becomes larger at constant $U(H)$ for harder continua (compare Figs. 5a and 5e).

2.5. $Z = 5 \, Z_\odot$

Using the baseline incident continuum shape and a cloud column density of $N(H) = 10^{23}$ cm$^{-2}$, we computed another grid assuming a metallicity of $5 \, Z_\odot$, similar to that deduced for some high-redshift quasars (Hamann & Ferland 1993; Ferland et al. 1997). We used the chemical
Fig. 4.- (a) Same as Fig. 3 for a column density of $10^{22}$ cm$^{-2}$ and a selection of six emission lines. (b) Same as Fig. 3 for a column density of $10^{23}$ cm$^{-2}$ and a selection of six emission lines. (c) Same as Fig. 3 for a column density of $10^{24}$ cm$^{-2}$ and a selection of six emission lines.
The abundances, by number relative to hydrogen, are the following:


The $W_\lambda$ distributions for the same six selected emission lines are shown in Figure 6. Comparing these results to those in Figure 4b (same incident continuum and cloud column density but solar abundances), one can see several important differences. First, the hydrogen and helium lines' peak $W_\lambda$-values are diminished at a metallicity of $Z = 5 Z_\odot$ by a modest amount (0.1–0.2 dex) compared to solar. This is because the metals become important opacity sources with increasing metallicity, replacing to a significant degree, hydrogen and helium. Second, the peak values of the O VI $\lambda1034$ and C IV $\lambda1549$ distributions are both diminished by about 0.4 dex. With increasing metallicity, Z, the nitrogen abundance scales like $Z^2$ (Hamann & Ferland 1993), and the cooling from carbon and oxygen is shifting over to nitrogen. In addition the strong metal opacity and accompanying lower electron temperatures shrink the emitting volumes of especially the higher ionization emission lines. See Ferland et al. (1996) for specific predictions regarding $N$ V, He II, and Z-dependent behavior.

2.6. Anisotropic Line Emission

Davidson & Netzer (1979) and Ferland et al. (1992) discussed the anisotropic line emission from clouds. O'Brien et
Fig. 4. (a) Same as Fig. 4(b) for a continuum spectral energy distribution whose UV bump peaks at 44 eV and has an 

(b) Same as Fig. 4(b) for a continuum spectral energy distribution whose UV bump peaks at 22 eV and has an 

(c) Same as Fig. 4(b) for a continuum spectral energy distribution whose UV bump peaks at 44 eV and has an 

(d) Same as Fig. 4(b) for a continuum spectral energy distribution whose UV bump peaks at 22 eV and has an 

(e) Same as Fig. 4(b) for a continuum spectral energy distribution whose UV bump peaks at 22 eV and has an 

\[ z_w = 1.20 \]

\[ z_w = 1.40 \]

\[ z_w = 1.60 \]
al. (1994) demonstrated the effects of this “line beaming” on the response functions and line profiles of the emission lines. In general, strong resonance lines, as well as optically thick excited state lines (e.g., $\text{H}\beta \lambda 4861$, $\text{He}\ II \lambda 1640$) will generally preferentially escape out the front sides of the clouds (i.e., the side facing the incident continuum). The conditions that lead to significant line beaming will differ for individual lines, depending mainly on the ionization and temperature structure. For example, $\text{Ly}_\alpha$ becomes fully anisotropic with the formation of a hydrogen ionization front within the cloud but nearly isotropic in clouds that are optically thin to hydrogen ionizing photons. Most other lines require more specific conditions and are not so “binary” in their inward/outward emission. In the case of $\text{C}\ IV \lambda 1549$, the degree of the anisotropy is approximately proportional to the ionization parameter. This is because the size of the ionized portion of the cloud, and thus the $\text{C}^3\ +$ column density, is proportional to $U(\text{H})$. This line also becomes more anisotropic with increasing gas density at constant ionization parameter, i.e., in the direction of thermalization. The two effects result in anisotropic emission for the following reason. Because the peak of the line source function within a cloud does not coincide with the position of the peak ion fraction (the former lies closer to the front face of the cloud where the temperature is higher), the line is beamed toward the continuum source. In general, harder continua produce $\text{C}\ IV$ (and other lines) more isothermally in this respect, and the line emission will be more isotropic than in clouds that are illuminated by softer continua.

In Figure 7, we show contours of constant logarithmic ratios of $F_{\text{line}}/F_{\text{total}}$ for $\text{C}\ IV \lambda 1549$, assuming the baseline continuum, solar abundances, and cloud column densities of $10^{23}$ cm$^{-2}$. The radiative transfer computations assume plane parallel slab clouds; the actual line beaming function may be more complicated depending on the cloud geometry, nonradial transfer, and other effects. A compari-
son with Figure 4b shows that clouds should emit C IV anisotropically where its strength is significant. Low-density clouds that are becoming fully ionized in hydrogen are nearly isotropic emitters (lower left corner), but are anisotropic emitters at larger gas densities (moving toward the upper right corner). Clouds optically thick to hydrogen ionizing photons beam C IV preferentially inward, with the beaming factor increasing as the line becomes thermalized. The steep gradient in the inward/total ratio along the upper diagonal boundary roughly coincides with the clouds becoming optically thin to 54 eV photons, and thus with the steep decline in the $W_1$(C IV). This boundary shifts with cloud column density; little else changes with changing column density in Figure 7. Other incident continuum shapes, different chemical abundances, and the presence of nonthermal motions would change the nature of the line beaming significantly, however.

3. CONCLUSIONS

We have presented these grids to quantitatively show the general dependence of the emission spectrum from individual BLR gas clouds to changes in the most important input parameters. While most of these trends will seem obvious in a qualitative sense, we hope that the diagrams presented here will help future researchers to navigate more easily through the $\Phi(H)$, $n(H)$, $N(H)$, continuum shape, metallicity parameter space.

The difference between the logarithmic equivalent width contour plots for two different lines will be logarithmic contours of the line intensity ratio, which is of considerable interest for analyzing observational data. These grids should also prove valuable to the detailed modeling of broad line regions, since all such models must include emissivity from a distribution in cloud properties.
We have chosen not to present intensity-ratio contour plots here (a subject of future work) but rather to make the numerical data from the equivalent width grids easily available over the Internet. These data are accessible via the CLOUDY home page (currently "http://www.pa.uky.edu/~gary/cloudy/`). A "readme" file describes the data files and will log their updates. The database contains the information, as plotted in Figure 3, for over 100 emission lines and diffuse continua in a 3 column ASCII format file for each emission line: log $n$(H), log $\Phi$(H), $W_{1216}/1216$. Information on how to convert a line's $W_{1216}/1216$ surface flux (useful for detailed modeling of the BLR) for a given incident continuum shape are provided. All of these are available for a variety of incident continuum shapes, many cloud column densities, a few sets of gas abundances, and other parameters.

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Fig. 7.—Contours of logarithmic inward to total emission-line flux ratios for C IV $1549$, assuming the baseline grid parameters. The most important contours are labeled, with $-0.30$ designating isotropic emission (inward/outward flux ratio $= 1.0$), and $-0.05$ designating clouds emitting C IV most anisotropically. The step size for the contours is 0.05 dex. See text for details.