Toward an Understanding of the Baldwin Effect

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Abstract. After a short review of the quasar problem and what we can hope to learn from their emission line spectra, I discuss the current body of knowledge concerning quasar emission lines and their relationships to the local and ionizing continua. I propose a hypothesis that the Baldwin effect is due to a characteristic relationship between the continuum spectral energy distribution, the gas metallicity (Z), and the quasar luminosity. I suggest that such a relationship might arise naturally from a scenario involving massive galaxy formation and evolution driving the birth and evolution of the quasar central engines in terms of four fundamental parameters: $M_{bh}$, $\dot{M}$, $\dot{M}/M_{bh}$, and Z.

1. Introduction

1.1. Some history

Quasars have long been mysterious points of light in our sky. Originally turning up as star-like radio sources in the early radio surveys of the late 1950s, their spectra remained a puzzle until Maarten Schmidt’s realization (Schmidt 1963) that their emission lines are as those seen in emission line galaxies (Seyfert 1943), but greatly redshifted. The “discovery object” was 3C 273 with a redshift of 0.158. This placed quasars billions of light years away and made them the most distant and luminous entities in the universe. As more were discovered, the redshift limit was pushed ever higher, meaning that we were probing ever-earlier epochs in our Universe’s history. Soon it was realized that if we could establish quasars as “standard luminosity candles”, we could determine their distances independent of their redshifts and thus determine the expansion history of the Universe. Thirty-five years later (my lifetime) we are still puzzling over the story that quasars are telling us.

1.2. The quasar paradigm

While a comprehensive understanding of the quasar phenomenon remains illusive, a standard model has emerged: a supermassive black hole in the nucleus of a massive galaxy accretes matter at rate $\dot{M}$, converting gravitational potential energy into light ($L = \eta \dot{M} c^2$; $\eta \sim 0.1$) and mechanical energy (Blandford & Rees 1978; Rees 1984). Evidence continues to trickle in that quasars represented a dynamically active stage in the lives of massive galaxies (McLeod & Riecke 1995a, 1995b; Bahcall et al. 1997; McLure et al. 1998), with the masses of their
central black holes related to the host galaxy’s halo mass (Haehnelt, Naras- 
jan, & Rees 1998; Laor 1998, and these proceedings). The rapid appearance of 
quasars with redshifts $z > 2$ was likely associated with massive galaxy formation 
(Boyle & Terlevich 1998; Haehnelt et al. 1998; Miller & Percival 1998; Silk 
& Rees 1998). Quasars are now extinct, though their low luminosity cousins, 
the Seyfert galaxies, are still found in the here and now. During their reign, the 
quasar “central engines” poured out tremendous numbers of UV/X-ray photons. 
In the standard model the mass of the central black hole and the mass accretion 
rate together determine the quasar’s luminosity and continuum spectral energy 
distribution (SED).

1.3. Quasar emission lines and the stories they tell

“Sometimes you can’t stick your head in the engine, so you have to examine 
the exhaust.” (Don Osterbrock c. 1987). The central engine of a quasar is 
manifested in the accretion of matter onto a supermassive black hole. This 
process releases energy, much of this in the form of light at ionizing energies 
(e.g., Mathews & Ferland 1987) which is generally unobservable due the opacity 
of the intergalactic and interstellar media. Therefore, we cannot discern directly 
how a large fraction of the energy in the central engine is dissipated. However, 
some of these continuum photons are intercepted by gas of unknown origin 
moving rapidly in the black hole’s gravitational potential. These photons ionize 
and heat this non-LTE gas, which responds by producing the quasar broad 
emission line spectrum. The recombination lines of Ly$\alpha$ $\lambda 1216$ and He II $\lambda 1640$ 
are a measure of the numbers of photons lying just shortward of 912 Å and 
228 Å, respectively. The ratio of the intensities of the strongest line coolant, 
C IV $\lambda 1549$, to the strongest recombination line, Ly$\alpha$, measures the cooling per 
recombination, or the heating per photoionization, and thus reflects the energy 
balance of the gas. Since the energy from the continuum source absorbed by 
the gas must equal the energy emitted by the gas, the emission lines serve as an 
indirect means to measure the ionizing continuum. This and the likelihood that 
the emission line widths are indicative of the central gravitational potential well 
mean that we can hope to learn from the emission lines the nature of the central 
engines of quasars.

Origin & Nature of the Emitting Gas. The emission line spectra of quasars 
must be leaving clues, albeit apparently subtle ones, as to the origin and nature 
of the emitting gas. For a discussion of this see my other contribution to these 
conference proceedings.

Chemical abundances. The strengths of the heavy element emission lines in 
even the highest redshift quasars give testimony to the heavy element enrichment 
from stellar evolution that had to occur within the first billion years of cosmic 
history. If they can be understood, quasar emission lines will elucidate the 
chemical evolution of galactic nuclei over the time span of $\sim 10\% – 90\%$ the age 
of the Universe (Hamann & Ferland 1993; Hamann & Ferland 1999; Hamann, 
these proceedings).

Quasar evolution. Quasars are known to have evolved in number density and 
luminosity over past 10 or so billion years. Their rapid rise at high redshifts
(presumably due to galaxy formation), their reign near $z \approx 2.5$, and their
demise at lower redshifts, as the source of gas “ran dry” and/or the accretion
mechanism itself failed (Haiman & Menou 1998), is reasonably well established
(Boyle, Shanks, & Peterson 1988; Boyle 1991; Hewett, Foltz, & Chaffee 1993;
Goldschmidt & Miller 1997; La Franca & Cristiani 1997; Graham, Clowes, &
Campusano 1998). Quasar evolution may be tied to the dynamical and chemical
evolution of massive galaxies (§1.2). But we do not understand these things at
the fundamental level. Quasar emission lines, mirroring the action occurring in
galactic nuclei, are keys to unlocking these mysteries.

Beacons of cosmic history? Since the 1970s we’ve known of the so-called “Lyα”
forest of absorption lines in the spectra of quasars representing matter along
the line of sight to the quasar. The statistics in number and character of the
Lyα forest demonstrate an evolution with look-back time in the gas that may
represent galaxies, protogalaxies, or failed galaxies. However, quasars themselves
are strewn throughout most of cosmic history and their intrinsic light must be
telling us something about that history. Their connection to galaxy evolution
is an example. Another is if their light could be somehow established as a
standard luminosity candle, we might establish the expansion history and fate
of the Universe. Detailed analysis of quasar spectra became possible in the late
1970s with the advent of sensitive electronic spectrographs. It was at this time
that a young astronomer by the name of Jack Baldwin was compiling spectral
characteristics of quasars, when he came across something interesting.

1.4. Observed line, continuum, & luminosity correlations
This is a brief summary of the situation. For a more complete review the reader
is directed to the conference proceedings contribution from Osmer & Shields.

The Baldwin Effect. Uncharacteristic of Galactic emission line sources (e.g.,
novae, PNe, H II regions), the spectra of quasars are remarkably homogeneous.
The same emission lines sitting atop a “blue bump” continuum, with similar in-
tensity ratios, are observed again and again — this, in the face of 4–5 orders of
magnitude in their luminosities and billions of years of lookback time. However,
upon comparison of the C IV emission line flux to that of the underlying con-
tinuum flux density $f_\lambda$, Jack discovered that this ratio is in inverse proportion
to the monochromatic ultraviolet continuum luminosity $L_{uv}$ (Baldwin 1977).

$$\log W_\lambda(C\ IV) \propto \beta \log L_{uv}, \ \beta < 0$$  

This effect is illustrated dramatically, though qualitatively, in Figure 1. If cal-
ibrated, a measurement of a quasar’s C IV equivalent width would indicate its
luminosity and thus its luminosity distance.

Since Baldwin’s initial discovery, several studies have found similar rela-
tionships for UV emission lines in addition to C IV, and that each emission
line has its own logarithmic slope in the $W_\lambda - L_{uv}$ relation, perhaps offering
clues to its origin (Baldwin, Wampler, & Gaskell 1989; Kinney, Rivolo, & Ko-
rathkar 1990; Zamorani et al. 1992; Espey, Lanzetta, & Turnshek 1993; Osmer,
Porter, & Green 1994; Laor et al. 1995; Zheng, Kriss, & Davidson 1995; Turn-
shek 1997). Kinney et al. (1990) also showed that the Baldwin effect extends
Figure 1. A qualitative illustration of the Baldwin effect. The solid curve is the continuum normalized mean UV spectrum of the Seyfert 1 nucleus of NGC 5548 ($z = 0.0174$) from the 1993 monitoring campaign (Korista et al. 1995). The dotted curve is a portion of the revised version of the composite quasar spectrum from the Large Bright Quasar Survey (Morris 1994), also continuum normalized. Effectively, $\sim 3$ orders of magnitude in UV continuum luminosity separate these two spectra. Note, too, that the narrow emission line spectrum is completely missing from the quasar composite. The blue wing of the Sy 1 Ly$\alpha$ profile is contaminated by geocoronal Ly$\alpha$, and in the quasar composite spectrum the region shortward of the peak of Ly$\alpha$ is affected by “Ly$\alpha$ forest” absorption. This is a log-log plot.
down to Seyfert nuclei luminosities. Unfortunately, many of these same studies also demonstrated the existence of substantial intrinsic scatter in the relations. Thus, the use of quasars as “beacons of cosmic history” via the Baldwin effect would have to await some understanding of quasar spectra.

Other correlations. A number of other important quasar spectral correlations have been amassed since Baldwin’s discovery in 1977 and these may provide clues to the latter’s origin.

Quasars are intrinsically luminous X-ray sources. A number of quasar X-ray emission studies have found a relationship between the UV/X-ray continuum flux ratio

\[ \frac{f_{uv}}{f_x} = (\frac{\nu_{uv}}{\nu_x})^{-\alpha_{uvx}} \]  \hspace{1cm} (2)

and the UV continuum luminosity \( L_{uv} \), in that higher luminosity quasars have characteristically steeper effective logarithmic UV to X-ray spectral slopes \( \alpha_{ox} \) (2500 Å – 2 keV) and \( \alpha_{uvx} \) (1350 Å – 1 keV) (Zamorani et al. 1981; Wilkes et al. 1994; Wang, Lu, & Zhu 1998). The Wilkes et al. (1994) relation is

\[ \alpha_{ox} \approx 1.53 + 0.11 \log \left( \frac{L_{\nu}(2500)}{10^{30}} \right) \]. \hspace{1cm} (3)

This relation extends down to the luminosities of Seyfert nuclei. It should be noted that the significance of this relationship is a subject of debate (LaFranca, Franceschini, & Vio 1995; Avni, Worrall, & Morgan 1995; Yuan, Siebert, & Brinkmann 1998).

Line ratios sensitive to the ionizing continuum SED, e.g., \( L_{\alpha}/C\ IV \) and \( L_{\gamma}/O\ VI \), and the equivalent widths of these three emission lines all correlate with \( \alpha_{ox} \) and \( \alpha_{uvx} \). This is an expected result based upon energetics arguments if \( \alpha_{ox} \) and \( \alpha_{uvx} \) are proxies for the actual ionizing continuum SEDs of quasars (Netzer, Laor, & Gondhalekar 1992; Zheng et al. 1995; Green 1996; Wang et al. 1998). As explained above these line ratios reflect the energy balance of the gas and thus broadly measure the average ionizing photon energy of the incident continuum. Relationships between \( L_{uv} \) and these line ratios and the line equivalent widths were also found in these studies.

Taken together, these correlations would indicate a general relationship between the quasar’s ionizing SED and its observed ultraviolet luminosity, and this may play a major role in the origin of the Baldwin effect.

2. “Natural Selection” and the emission line spectra of quasars

2.1. Emission line spectrum from a single cloud

The emission lines of quasars arise mainly or exclusively via the photoionization of gas, in the so-called broad line region, surrounding a UV/X-ray ionizing continuum source. Early successful photoionization models of emission from single clouds are described in the works of Davidson & Netzer (1979) and Kwan & Krolik (1981). The incident continuum SED and gas chemical abundances are the basic “raw materials” from which the emitted spectrum from a single cloud arises. For a given set of raw materials, the ionizing photon flux, the gas density,
and especially the ratio of these two parameters — proportional to the ionization parameter $U(H)$ — set the spectrum. The gas column density and details concerning the radiation transfer place the final touches on the emitted spectrum. The early models found that there was a preferred value of $U(H) \approx 0.01$, though a separate population of gas with a larger value must also exist to account for the observed strength of the O VI $\lambda$1034 line.

### 2.2. An observational paradox and its resolution

The work of many observational spectroscopists of the late 1970s and early 1980s demonstrated the homogeneous nature of the emission line spectra of quasars and their lower luminosity cousins, Seyfert nuclei. Nature must somehow know to adjust the ionization parameter knob to the nearly the same value through 5 decades in luminosity and 10 billion years of lookback time.

From the mid 1980s to the mid 1990s, the monitoring of Seyfert nuclei variability and emission line reverberation (Peterson 1993) demonstrated that the broad line regions lie nearer to their continuum sources than thought earlier, and contain gas with a range of particle densities to accommodate a range in ionization through a region that spans at least $\sim 1.5$ decades in radius. Rees, Netzer, & Ferland (1989) and Goad, O'Brien, & Gondhalekar (1993) and others explored models in which the gas density and column density were unique to and allowed to vary with the distance from the ionizing photon source. However, the means by which the quasar normalizes its gas properties or why one power law of gas properties is chosen over another remained unknown. Somehow, over a huge range in ionizing continuum luminosity, gas that is broadly distributed in space, particle density, and ionization is able to produce the same sets of emission lines in roughly similar ratios. What’s going on?

In the history of quasar photoionization models, the “single cloud” model was followed by the “two cloud” model, and then a radial power law in cloud properties. Recently, Baldwin et al. (1995) extended the “multi-cloud” idea to its next logical step: “Locally Optimally-Emitting Clouds (LOC).” What if nature provides the broad line regions with a large pool of gas properties, such that at every radius there exists a large range in particle and column densities? Under these conditions the emitted spectrum is controlled by powerful selection effects introduced by the atomic physics and basic radiative transfer effects. See Figure 2 and Korista, Baldwin, & Ferland (1997). Gas having properties that make it most efficient in reprocessing the continuum into a particular line will emit most of that line’s luminosity. The gas need not fill the entire $n(H) - \Phi(H)$ plane in Figure 2, but unless the gas in the BLR has a remarkably restricted range of properties, we will in fact observe the optimally emitting gas for most lines. And just as important, such an ensemble spectrum reproduces a typical quasar spectrum.

The LOC model suggests that at work is a loose analog of Darwin’s natural selection and it offers natural explanations for: (1) the observed homogeneity of the quasar spectra and the “magic ionization parameter” problem, and (2) the ionization stratification inferred from observations. Another important consequence of this idea is that to a good approximation we can take a “statistical mechanics” approach to the modelling of quasar spectra, concerning ourselves with the ensemble emission, rather than with the details of the properties and
Figure 2. Contours of log $W_\lambda$, referenced to the incident continuum at 1215 Å and for full source coverage, for six emission lines (or blends) are shown as a function of the hydrogen density and flux of hydrogen ionizing photons. The total hydrogen column density is $10^{23}$ cm$^{-2}$. The $W_\lambda$ is in direct proportion to the continuum reprocessing efficiency. The smallest (generally outermost decade contour corresponds to 1 Å, each solid line is 1 decade, and dotted lines represent 0.2 decade steps. The contours generally decrease monotonically from the peak (solid triangle) to the 1 Å contour. The solid star is a reference point marking the old “standard BLR” parameters. “Sum Ly$\alpha$ 1216” is the sum of Ly$\alpha$ 1216, He II 1216, and O V] 1218.
arrangement of the individual gas clouds. In this picture the continuum SED and gas chemical abundances are the major drivers of the emission line spectrum, not a magic ionization parameter. In this case we can hope to learn about these two fundamental parameters and the possible stories they can tell concerning cosmic history and the nature of quasars.

A word of caution should appear here. The emission line spectrum from gas distributed in particle density and radius is in general much less sensitive to changes in the gas abundances and continuum SED than that emitted by a single “cloud” of fixed particle density and ionization parameter. This is because that as a cloud’s thermodynamics adjusts to changes in the SED or gas abundances, its reprocessing efficiency can change immensely. In any distributed cloud model, there will be other clouds with other properties at similar distances from the ionizing source that will also react, and the integrated response is dampened. Under the distributed cloud hypothesis, the emitted spectrum does remain sensitive to the continuum SED and gas abundances, and this sensitivity will probably better represent nature.

3. What are the parameters that govern the Baldwin Effect?

I use the spectral synthesis code, Cloudy (90.04; Ferland et al. 1998), and the emission from an ensemble of plane-parallel clouds under the assumption of the LOC model to demonstrate that a characteristic dependence of the continuum SED and gas abundances on the quasar luminosity may provide an explanation for the Baldwin effect. For simplicity and because of the spectrum’s general insensitivity to it, I held the column density fixed at \( N(H) = 10^{23} \text{ cm}^{-2} \). See Korista, Baldwin, & Ferland (1998) for details.

3.1. The continuum SED

For reasons of simplicity and because we do not know what ionizing continuum SED is incident upon the broad line emitting gas, I will demonstrate the effects of a changing continuum SED on the gas emission using simple power laws, their spectral indeces \( \alpha \) ranging from \(-2\) to \(-1\) (\( F_{\nu} \propto \nu^{\alpha} \)).

Panel (b) of Figure 3 shows how the equivalent widths (here, always measured with respect to the continuum at 1215 Å) of 5 prominent quasar emission lines vary with the power law index. The gas abundances were fixed to roughly solar values in all cases. The emission line equivalent widths (\( W_{\lambda} \)) all diminish with the softening in the continuum. This is simply a result of conservation of energy — fewer high energy ionizing photons and the resulting lower gas temperatures produce weaker lines relative to the non-ionizing UV continuum at 1215 Å. Panel (d) of Figure 3 shows that ratios \( \text{Ly} \alpha / \text{O VI} \) and \( \text{Ly} \alpha / \text{C IV} \) are highly sensitive to the continuum SED, but that \( N \text{ V/He II} \) and especially \( N \text{ V/C IV} \) are not. Other SED-insensitive line ratios are \( \lambda 1900 \text{ blend/C IV}, \lambda 1400 \text{ blend/C IV}, \) and \( N \text{ III 990/C III 977} \).

Figure 4 compares our simulations for fixed gas abundances to the observations of \( \text{Ly} \alpha / \text{O VI} \) (Zheng et al. 1995) and \( \text{Ly} \alpha / \text{C IV} \) (Wang et al. 1998). The observational points used measurements of \( \alpha_{\text{ox}} \) and \( \alpha_{\text{uvx}} \), while of course the simulations have assumed a simple power law with index \( \alpha \). The correspon-
dence is good and demonstrates that the observed $\alpha_{\text{ox}}$ and $\alpha_{\text{uv}}$ must stand as reasonably good proxies for the true ionizing continuum SED.

Zheng & Malkan (1993) proposed that the Baldwin effect could be explained via the combined effect of a strengthening non-ionizing UV continuum and weakening ionizing continuum with luminosity. That the higher ionization lines in Figure 3b have steeper $W_{\lambda}$ dependencies on the spectral index is a reflection of these two effects, and is generally consistent with the trends in the measured slopes of the Baldwin effects of various emission lines (Espey et al. 1993; Espey, these proceedings).

A SED–$L_{\text{uv}}$ relationship might be driving the Baldwin effect, but it cannot be the whole story. When the $W_{\lambda}(\text{N} \, \text{V})$ is measured it has little or no dependence upon luminosity (Espey et al. 1993; Osmer et al. 1994; Laor et al. 1995). Figure 1 illustrates this further. Panels (b) and (d) of Figure 3 predict that N V/C IV should be luminosity independent, i.e., N V should show a Baldwin effect as strong as C IV. Hamann & Ferland (1993) showed that larger values of N V/C IV and N IV/He II are systematically found at larger quasar luminosities. This must mean that the continuum shape is not the only parameter.

### 3.2. Metallicity

Here I will demonstrate the effects of a changing gas metallicity, $Z$, for a fixed continuum SED ($\alpha = -1.4$). In a simple scheme to change the metallicity I assumed that the metal abundances relative to hydrogen scale from their solar values as $Z$. However, nitrogen is expected to be selectively enhanced by “secondary” CNO processing in stellar populations (at least when $Z$ exceeds a few-tenths solar), and so in these simulations $(\text{N}/\text{H}) \propto Z^2$ while $(\text{N}/\text{C}) \propto Z$ and $(\text{N}/\text{O}) \propto Z$ (Hamann & Ferland 1993; Vila-Costas & Edmunds 1993; van Zee, Salzer, & Haynes 1998). As such, nitrogen lines are valuable tracers of the gas chemical enrichment (Ferland et al. 1996).

In panel (a) of Figure 3 I show how the equivalent widths of the same five emission lines vary with the metallicity. The strengths of Ly$\alpha$ and especially He II diminish with the increasing metal opacity. In as far as hydrogen and helium are still the major opacity sources, their ionized volumes diminish with increasing $Z$ due to the increased numbers of electron donors. For $Z > Z_{\odot}$, the strengths of C IV and O VI both diminish as the gas cools and the cooling shifts to other lines. However, since N V is initially a weak line and because the N/H abundance ratio is proportional to $Z^2$, $W_{\lambda}(\text{N} \, \text{V}) \propto Z!$ Other initially weak lines are generally correlated to a lesser extent with metallicity. However, those lines that are formed near the front of the cloud (e.g., O IV 1402) remain roughly constant with $Z$. The temperatures here scale strongly with $Z$ (i.e., cooler with increasing $Z$) and the He$^{++}$ zone where these lines form is diminished in volume.

In panel (c) of Figure 3 I show the variations in the same five line ratios with metallicity. For reasons given above, Ly$\alpha$/O VI and Ly$\alpha$/C IV are relatively insensitive to the gas metallicity. However, the N V/He II and N V/C IV ratios are roughly linear in $Z$. We also find the following rough dependencies on metallicity: $\lambda 1900$/C IV $\propto Z^{0.6}$, N III 990/C III 977 $\propto Z$, and $\lambda 1400$/C IV $\propto Z^{0.3}$.

It is worth noting that the same line ratios that are insensitive to the continuum SED are sensitive to $Z$, and those sensitive to the continuum SED are
Figure 3. The equivalent widths of 5 prominent quasar emission lines and their ratios as a function of metallicity ($Z$; panels [a], [c]) for a fixed continuum SED ($\alpha = -1.4$), and as a function of the power law index of the continuum SED ($\alpha$; panels [b], [d]) at a fixed gas metallicity ($Z = 1$).
Figure 4. Observed emission line ratios vs. $\alpha_{ox}$ (solid dots) and predicted emission line ratios vs. $\alpha$ (solid lines).
insensitive to $Z$. While the relationship is not always simple, this dichotomy of emission line ratio properties is not a coincidence, and may prove to be a powerful tool in disentangling the effects of these two fundamental parameters on the quasar spectrum.

### 3.3. An explanation?

Panels (a) and (b) of Figure 3 suggest a solution to the N V conundrum. If, characteristically, the gas metallicity increases (with $N/H \propto Z^2$) while the continuum SED softens with increasing luminosity, the $W_\lambda(N\,V)$ will remain approximately constant and $N\,V/C\,IV$ and $N\,V/He\,II$ will increase with luminosity, as observed.

The models do not tell us how to link the SED and $L_{uv}$ together, so I adopted the empirical $\alpha_{ox} - L_{uv}$ relation found by Wilkes et al. (1994; $H_0 = 50$ km s$^{-1}$ Mpc$^{-1}$ and $q_0 = 0$), and adjusted slightly the logarithmic zero point to reference the continuum at 1550 Å. Guided by the $N\,V/He\,II$, $N\,V/C\,IV$, and $L_{uv}$ relations found by Hamann & Ferland (1993) I guessed a $L_{uv} - Z$ relation: $Z \approx 1$ for the lowest luminosity quasars (i.e., Seyfert nuclei) and $Z \approx 10$ for the highest luminosity quasars. In this way I adopted the following simple relation to represent the hypothesis:

$$\log Z = 0.183 \log \left( \frac{L_{\nu}(1550)}{10^{30}} \right) + 0.477. \tag{4}$$

After coupling the adopted SED – $L_{uv}$ and $Z - L_{uv}$ relations, the photoionization simulations then predict the slopes, $\beta$, of the Baldwin effect for the different emission lines and blends. We show these in Table 1, in descending order of the ions’ destruction ionization potentials.

| Emission Line | $\beta$ |
|---------------|--------|
| O VI $\lambda 1034$ | -0.22 |
| N V $\lambda 1240$ | -0.047 |
| C IV $\lambda 1549$ | -0.20 |
| He II $\lambda 1640$ | -0.17 |
| $\lambda 1400$ | -0.13 |
| $\lambda 1900$ | -0.083 |
| Mg II $\lambda 2800$ | -0.092 |
| Ly$\alpha$ $\lambda 1216$ | -0.10 |

The predictions in Table 1 follow both the measured amplitudes and trends of the Baldwin effect slopes reported in the literature (Baldwin, Wampler, & Gaskell 1989; Kinney, Rivolo, & Koratkar 1990; Zamorani et al. 1992; Espey, Lanzetta, & Turnshek 1993; Osmer, Porter, & Green 1994; Laor et al. 1995; Zheng, Kriss, & Davidson 1995; Turnshek 1997). Note, however, that it is difficult to compare results from different works since the investigators assumed different values of $q_0$ whose effect is non-uniform in the $W_\lambda - L_{uv}$ plane. Variations in slope due to different assumptions of $q_0$ are at the 0.04 decade level, comparable to the typically quoted uncertainties in the measured slopes.
The interplay of the luminosity dependent SED – $Z$ effects determines the spectrum, and accounts for the differing Baldwin effect slopes amongst the different emission lines. While it has been suggested that the observed strengthening of the Ly$\alpha$/C IV and $\lambda$1900/C IV ratios with luminosity implies a shift to lower ionization parameters with increasing quasar luminosity (e.g., Mushotzky & Ferland 1984), I would argue for characteristic shifts to softer continuum SEDs and larger values of $Z$. The predicted changes in Ly$\alpha$/C IV with $L_{uv}$ are dominated by a shift in the continuum SED, while changes in $\lambda$1900/C IV are dominated by changes in $Z$.

4. Discussion

While I have shown that a SED – $Z$ – $L_{uv}$ relationship holds promise in explaining the origin of the Baldwin effect, the SED – $L_{uv}$ and $Z$ – $L_{uv}$ relations or at least their combined effect must be firmly established and then calibrated, before we can hope to understand what the Baldwin effect can tell us about cosmology or cosmic history. I have presented several emission line ratios that should provide the means to disentangle the effects of the continuum SED and $Z$.

But why should we expect a SED – $Z$ – $L_{uv}$ relationship? We are beginning to see quasars in the context of the environment of massive galaxies (§ 1), rather than isolated, exotic beasts. The co-evolution of massive galaxies and the quasars within them may offer an answer to the above question, and thus may be the fundamental origin of the Baldwin effect in quasar spectra. Below, I try to summarize this emerging, yet, I caution, immature picture.

10 $> z >$ 2. The rapid turn on of quasars was the result of massive galaxy formation, during which the action of merging halos (Press & Schecter 1974) both created and drove gas into supermassive black holes (Haehnelt, Natarajan, & Rees 1998; Miller & Percival 1998). Masses of the nuclear black holes, $M_{bh}$, correlated with masses of forming galaxies or their dark halo masses (Haehnelt et al. 1998). More massive galaxies, with their deeper central gravitational wells, were better able to retain gas deposited during stellar evolution than were lower mass galaxies, so they had a more rapid buildup of the heavy elements in their nuclear regions (Hamann & Ferland 1993; 1999). The most massive black holes likely produced the most luminous quasars, initially, since quasars turned on near or above their Eddington limits: $L/L_{Edd} \propto M/M_{bh} \geq 1$. These most luminous quasars thus required the largest mass accretion rates, $\dot{M}$, to sustain their luminosities. While we are far from understanding the mechanisms that generate the quasar continua (see Antonucci 1988; 1998), the standard accretion models predict softer UV bumps for larger $M_{bh}$ at a fixed $\dot{M}/M_{bh} \propto L/L_{Edd}$ (Laor & Netzer 1989; Sincell & Krolik 1998), and the current corona – accretion disk models predict larger UV to X-ray continuum flux ratios for larger values of $\dot{M}/M_{bh}$ (Czerny, Witt, & Życki 1996). Therefore, more luminous quasars might be expected to have typically softer continuum SEDs (e.g., steeper $\alpha_{ox}$). With the largest required mass accretion rates, the most massive and luminous quasars are expected to have the shortest lifetimes (like massive stars), as the limited “fuel” supply is exhausted. The fuel exhaustion process is not well understood, but there are some ideas. At sufficient luminosities relative to the disk
binding energy, a “back reaction” may occur, choking off the matter accretion significantly (Haehnelt et al. 1998). Furthermore, the self-similar infall solutions of Bertchinger (1985) and the Press-Schecter theory of the collapse of dark matter halos (1974) both predict a decline in the mass accretion rate with time. Even if $\dot{M}$ were to remain constant, the ratio $\dot{M}/M_{\text{bh}}$ must evolve to smaller values due to accretion alone. Thus the evolution of an accreting black hole quite naturally leads to a drop in $\dot{M}/M_{\text{bh}}$ with time (see also Haiman & Menou 1998). Once $\dot{M}/M_{\text{bh}}$ drops below a critical value, the accretion flow radiation efficiency is expected to drop to values $\eta \ll 0.1$, and an advection dominated accretion flow (ADAF) may result (Narayan & Yi 1995). In this mode, the UV to X-ray continuum luminosities are expected to be more comparable. Thus, as $\dot{M}/M_{\text{bh}}$ in individual quasars diminished with time, evolution to lower luminosities and harder continuum SEDs (e.g., flatter $\alpha_{\text{ox}}$) likely resulted (Caditz, Petrosian, & Wandel 1991; Yi 1996; Haehnelt et al. 1998).

$z < 2$. By this time most of the massive galaxies had already formed and so the major fireworks were over — most quasars had begun their death march, dying of exhaustion. The peak in the active black hole mass function likely slipped slowly to smaller values with time (Siemiginowska & Elvis 1997), and with it the corresponding required $\dot{M}$, perhaps allowing for longer quasar lifetimes. The typical quasar SED would evolve as discussed above. The initial nuclear gas metallicity would be characteristically smaller in the shallower potential wells of the lower mass black holes. Further evolution to smaller values in $Z$ might have occurred in quasars of any mass due to dilution by lower $Z$ gas falling into the nuclear regions over the life of the galaxy (Hamann & Ferland 1993). Later epoch galaxy mergers could rekindle the nuclear fires and again enrich the gas, temporarily extending the quasar epoch. But in a maturing and expanding universe, galaxy merger rates slowed, and eventually all quasars died. Remaining are the Seyfert nuclei with their typically smaller $M_{\text{bh}}$, $\dot{M}$, and $\dot{M}/M_{\text{bh}}$, lying within the centers of more modest galaxies, whose nuclear gas metallicities are within a factor of 2 of solar. Also present are the more massive, yet generally dormant, black holes in the nuclei of present-day giant elliptical and other galaxies (Margorrian et al. 1998).

The above picture is presently sketchy at best, and may be completely wrong. Key uncertainties are: the lives of quasars and their energy dissipation mechanism(s), galaxy formation and its relation to the births of the quasars. If this picture has any validity it is easy to see why the Baldwin effect has been such a hard nut to crack. Different initial conditions and times of massive galaxy formation resulted in separate quasar populations, characterized by $M_{\text{bh}}$, $\dot{M}$, $\dot{M}/M_{\text{bh}}$, and $Z$, co-evolving in time. This scenario suggests that these four parameters are fundamental to the quasar in driving its continuum and emission line spectra. Osmer, Porter, & Green (1994) demonstrated that the Baldwin effect is seen globally across all redshifts and within narrow redshift intervals. This would argue for the study of carefully selected samples of quasars at many redshift or lookback time intervals.

Further sources of intrinsic scatter in any continuum – emission line correlations can arise from geometry – orientation effects due to possible anisotropies in the line and continuum emission (Netzer 1987; Netzer et al. 1992), as well as short time scale continuum – emission line reverberation (Kinney et al. 1990;
Pogge & Peterson 1992; Shields, Ferland, & Peterson 1995). The latter should be less important for the higher luminosity quasars. These and other nuisances should “average out” in large samples of objects — and perhaps the luminosity distances can be recovered through a process analogous to “main sequence fitting” of stellar clusters, as suggested by Jack Baldwin at this meeting. For a thorough discussion of these issues, see the conference proceedings contribution of Osmer & Shields.

While the jury is still out as to whether the Baldwin effect in quasar spectra can ever be used as a standard luminosity candle, it may be telling us about the workings of the quasar central engine, the gas enrichment in the nuclei of massive galaxies, and possibly about the evolution of massive galaxies themselves.

Acknowledgments. Jack Baldwin and Gary Ferland are my collaborators in the work presented here. I also acknowledge helpful discussions with Fred Hamann and Joe Shields. I am grateful to the Baldwin family for their gracious hospitality during my two week stay in La Serena.

References
Antonucci, R. 1988, in Supermassive Black Holes, ed. M. Kafatos, (Cambridge, England: Cambridge Univ. Press)
Antonucci, R. 1998, preprint, astro-ph/9810067
Avni, Y., Worrall, D.M., & Morgan, W.A., Jr. 1995, ApJ, 454, 673.
Bahcall, J.N., Kirhakos, S., Saxe, D.H., & Schneider, D.P. 1997, ApJ, 479, 642
Baldwin, J.A. 1977, ApJ, 214, 769
Baldwin, J.A., Wampler, E.J., & Gaskell, C.M. 1989, ApJ, 338, 630
Baldwin, J.A., Ferland, G.J., Korista, K.T., & Verner, D. 1995, ApJ, 455, L119
Bertschinger, E. 1985, ApJS, 58, 39
Blandford, R.D., & Rees, M.J. 1978, in Pittsburgh Conference on BL Lac Objects, ed. A.M. Wolfe (University of Pittsburgh: Pittsburgh)
Boyle, B.J., Shanks, T., & Peterson, B.A. 1988, MNRAS, 235, 935
Boyle, B.J., & Terlevich, R.J. 1998, MNRAS, 293, L49
Boyle, B.J., et al. 1991, in ASP Conf. Ser. 21, The Space Distribution of Quasars, ed. D. Crampton (San Francisco: ASP), 191
Caditz, D.M., Petrosian, V., & Wandel, A. 1991, ApJ, 372, L63
Czerny, B., Witt, H.J., & Życki, P.T. 1996, preprint astro-ph/9609180
Davidson, K. & Netzer, H. 1979, Rep. Prog. in Physics 51, 715
Espey, B.R., Lanzetta, K.M., & Turnshek, D.A. 1993, BAAS, 25, 1448
Ferland, G.J., Baldwin, J.A., Korista, K.T., Hamann, F., Carswell, R.F., Phillips, M., Wilkes, B., & Williams, R.E. 1996, ApJ, 461, 683
Ferland, G.J., Korista, K.T., Verner, D.A., Ferguson, J.W., Kingdon, J.B., & Verner, E.M. 1998, PASP, 110, 761
Goad, M.R., O’Brien, P.T., & Goudhalekar, P.M. 1993, MNRAS, 263, 149
Goldschmidt, P., & Miller, L. 1998, MNRAS, 293, 107
Graham, M.J., Clowes, R.G., & Campusano, L.E. 1998, preprint astro-ph/9810037
Green, P.J. 1996, ApJ, 467, 61
Haeemelt, M.G., Natarajan, P., & Rees, M.J. 1998, MNRAS, in press
Haiman, Z., & Menou, K. 1998, ApJ, submitted, preprint astro-ph/9810426
Hamann, F., & Ferland, G.J. 1993, ApJ, 418, 11
Hamann, F., & Ferland, G.J. 1999, ARA&A, in press
Hewett, P.C., Foltz, C.B., & Chaffee, F.H. 1993, ApJ, 406, L43
Kinney, A.L., Rivolo, A.R., & Koratkar A.P. 1990, ApJ, 357, 338
Korista, K.T., Baldwin, J.A., & Ferland, G.J. 1997, ApJS, 108, 401
Korista, Kirk, Baldwin, Jack, Ferland, Gary 1998, ApJ, 507, 24
Korista, K.T., et al. 1995, ApJS, 97, 285
Kwan, J., & Krolik, J.H. 1981, ApJ, 250, 478
La Franca, & Cristiani, S. 1997, AJ, 113, 1517
La Franca, F., Franceschini, A., & Vio, R. 1995, A&A, 299, 19.
Laor, A. 1998, ApJ, 505, 83
Laor, A., Bahcall, J.N., Jannuzi, B.T., Schneider, D.P., & Green, R.F. 1995, ApJS, 97, 285
Laor, A., Jannuzi, B.T., Green, R.F., & Boroson, T.A. 1997, ApJ, 489, 656
Margorrian, J., et al. 1998, AJ, 115, 2285
Mathews, W.G., & Ferland, G.J. 1987, ApJ, 323, 456
McLeod, K.K., & Rieke, G.H. 1995a, ApJ, 441, 96
McLeod, K.K., & Rieke, G.H. 1995b, ApJ, 454, L77
McLure, R. et al. 1998, preprint astro-ph/9809030
Miller, L., & Percival, W.J. 1998, preprint astro-ph/9809322
Morris, S.L. 1994, private communication
Mushotzky, R., & Ferland, G.J. 1984, ApJ, 278, 558
Narayan, R., & Yi, I. 1995, ApJ, 452, 710
Netzer, H. 1987, MNRAS, 225, 55
Netzer, H., Laor, Ar., & Gondhalekar, P.M. 1992, MNRAS, 254, 15
Osmer, P.S., Porter, A.C., & Green, R.F. 1994, ApJ, 436, 678
Peterson, B.M. 1993, PASP, 105, 247
Pogge, R.W., & Peterson, B.M. 1992, AJ, 103, 1084
Press, W.H., & Schecter, P.L. 1974, ApJ, 181, 425
Rees, M.J. 1984, ARA&A, 22, 471
Rees, M.J., Netzer, H., & Ferland, G.J. 1989, ApJ, 347, 640
Schmidt, M. 1963, Nature, 197, 1040
Seyfert, K. 1943, ApJ, 97, 28
Shields, J.C., Ferland, G.J., & Peterson, B.M. 1995, ApJ, 441, 507
Siemigniowska, A., & Elvis, M. 1997, ApJ, 482, L9
Silk, J., & Rees, M.J. 1998, A&A, 331, 1
Sincell, M., & Krolik, J.H. 1998, ApJ, 496, 737
Turnshek, D.A. 1997, in ASP Conf. Ser. 128, Mass Ejection from AGN, ed. N. Arav, I. Shlosman, & R.J. Weymann (San Francisco: ASP), 52
van Zee, L., Salzer, J.J., & Haynes, M.P. 1998, ApJ, 497, L1
Vila-Costas, M.B., & Edmunds, M.G. 1993, MNRAS, 265, 199
Wang, T.-G., Lu, Y.-J., & Zhou, Y.-Y. 1998, ApJ, 493, 1
Wilkes, B.J., Tananbaum, H., Worrall, D.M., Avni, Y., Oey, M.S., & Flanagan, J. 1994, ApJS, 92, 53
Yi, I. 1996, ApJ, 473, 645
Yuan, W., Siebert, J., & Brinkmann, W. 1998, A&A, 334, 498
Zamorani, G., et al. 1981, ApJ, 245, 357
Zamorani, G., Marano, B., Mignoli, M., Zitelli, V., & Boyle, B.J. 1992, MNRAS, 256, 238
Zheng, W., & Malkan, M.A. 1993, ApJ, 415, 517
Zheng, W., Kriss, G.A., & Davidson, A.F. 1995, ApJ, 440, 606