Evolutionary Baldwin Effect in AGN

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Abstract.

Assuming Active Galactic Nuclei are powered by accretion onto a massive black hole we suggest that the growth of the central black hole mass due to the matter accreted over the AGN lifetime causes evolution of the luminosity and spectrum.

We show that the effective temperature of the UV continuum spectrum is likely to be anti-correlated with the black hole mass and with the luminosity. We estimate the change in the equivalent width of the emission lines due to the growth of the black hole and show that for plausible evolutionary tracks and effective temperature models the equivalent width is anti-correlated with continuum luminosity thus implying an evolutionary origin to the Baldwin effect.

1. Introduction

The most accepted explanation for the energy source of quasars and Active Galactic Nuclei (AGN) is the accretion of matter onto supermassive black holes in the center of the host galaxy. The amount of accreted matter required to explain the observed energy output is 0.001-few solar masses per year, while the central mass required to maintain steady accretion (the Eddington limit) is of the order of $10^6 - 10^9 M_\odot \text{yr}^{-1}$. Comparing these two numbers gives an age of $\sim 10^7 - 10^9$ years, which indicates a timescale for the evolution of the black hole mass and the AGN properties.

Conservation of angular momentum directs the accreted material to form a disk around the central black hole and the properties of such an accretion disk may be calculated under a few basic assumptions (e.g. Sakura and Sunyaev, 1973). In particular one can calculate the luminosity and spectral distribution of the radiation from the accretion disk, given the black hole mass and the accretion rate.

As the black hole mass grows due to the accreted material, the luminosity and the emerging spectrum change with time. Since the continuum radiation ionizes the line-emitting material and drives the broad AGN emission-lines, the change in the properties of the radiation from the central source changes also the properties of the emission lines. In particular the spectral shape of the ionizing radiation would determine the equivalent width (the ratio between the energy flux in the line to the continuum energy flux at the line frequency) of the emission-lines.
Baldwin (1977) showed that the equivalent width of the CIV emission-line decreases with increasing continuum luminosity, a correlation known as the 'Baldwin effect'. A similar relation has been found also for other broad emission-lines. The origin of this effect is not understood.

In this work we suggest that at least part of the Baldwin effect can be attributed to evolution. We estimate the relation between the equivalent width and the continuum spectrum, and calculating the evolution of the continuum emission from the accretion disk we show that for plausible evolutionary tracks the equivalent width is anti-correlated with the continuum luminosity.

2. Basic relations for accreting black holes

The basic properties of a compact, accretion powered radiation source must obey several basic relations:

**a. The Eddington limit:** in order to maintain steady spherical accretion the luminosity must be less than the Eddington luminosity,

\[ L < L_{Edd} = 4\pi G M m_p c / \sigma_T = 1.310^{46} M_8 \text{ erg/sec} \]

or

\[ M_8 = 0.7\eta^{-1} L_{46} \]  

where \( M_8 = M/10^8 M_\odot, \eta = L/L_{Edd} \) is the Eddington ratio, and \( L_{46} = L/10^{46} \text{ erg/sec} \).

**b. The black body temperature:** if a luminosity \( L \) comes from a region of radius \( R \) and temperature \( T \), then

\[ L < 4\pi R^2 \sigma T^4. \]  

If a spectral feature at a photon energy of \( E \) is due to black body emission from a region of size \( R \), then the temperature is given by \( E \approx 3kT \) and reversing the relation above we have an upper limit on the black hole mass (for a true black body spectrum this becomes an approximate equality):

\[ M_8 > 130E_{Ryd}^{-2} L_{46}^{-1/2} (R/R_s)^{-1} \]

where \( R_s = 2GM/c^2 \approx 3 \times 10^{13} M_8 \) cm is the Schwartzshild radius and \( E_{Ryd} \) is the spectral energy in Rydbergs.

Combining eqs. 1 and 3 we can eliminate \( M \) obtaining (for black body emission) an estimate of the size:

\[ \frac{R}{R_s} \approx 200L_{46}^{-1/2} \eta E_{Ryd}^{-2} \]

**c. Variability:** the shortest time scale for global variations in the luminosity is the light travel time across the Schwartzshild radius, hence if the luminosity is observed to vary significantly on a time scale \( \delta t \), the black hole mass has to be

\[ M_8 < (\delta t/10^3 r^{-1} \text{ sec}) \]
where \( r \) is the effective radius of emission in units of \( R_s \).

However, for continuum changes near the feature of spectral energy \( E \) the light travel time is (from eq. 3)

\[
\delta t_l \approx 1.3 \times 10^5 L_{46}^{1/2} E_{Ryd}^{-2/2} \text{sec},
\]
and the dynamical time is

\[
\delta t_d \approx 20 L_{46}^{1/4} \eta^{1/2} E_{Ryd}^{-3} \text{days},
\]
which gives time scales of the order of the observed UV variability in Seyferts and quasars.

d. Evolution of the black hole mass: We may define the Eddington time \( t_E \) as the time required for an accretion-powered object radiating at the Eddington luminosity to double its mass, due to accreted matter, \( t_E = M c^2 / L_E = 4 \times 10^8 \text{y} \). The observed luminosity implies an accretion rate of \( \dot{M} = 0.16 \epsilon^{-1} L_{46} M_{\odot} \text{y}^{-1} \) where \( \epsilon \) is the efficiency. Combining these two expressions gives the mass, accumulated if the accretion rate is maintained during a time \( t_E \):

\[
M_8 = 0.6 \epsilon^{-1} (L / L_{Edd})^{-1} f_L L_{46}
\]
where \( f_L \) is the fraction of the active time for intermittently active AGN.

3. The thin accretion-disk model

Many authors tried to fit accretion disk spectra to the observed AGN continuum, thus finding the accretion disk parameters \( (M, \dot{M}, \alpha) \) and the angular momentum of the black hole (Schwartzshild or Kerr) which best fit the observed continuum in the UV (Wandel and Petrosian 1988; Sun and Malkan 1991) or in the soft X-rays (Laor 1990).

3.1. The accretion disk spectrum

The radiative energy output of the accretion disk is dominated by the release of gravitational potential energy, the rate of which is \( GM \dot{M} / r \). A more accurate calculation yields

\[
L(R) = \frac{3GM \dot{M}}{8\pi R^3} \left[ 1 - \left( \frac{R_{in}}{R} \right)^{1/2} \right]
\]

where \( R_{in} \) is the inner disk radius. In the outer part of the thin disk the opacity is dominated by true absorption and the local spectrum is a black body spectrum. For this part of the disk, comparing eq. 3 to the black body radiation flux gives for the disk surface temperature

\[
T(R) \approx \left( \frac{3GM \dot{M}}{8\pi \sigma R^3} \right)^{1/4} \approx 6 \times 10^5 \left( \frac{\dot{m}}{M_8} \right)^{1/4} r^{-3/4} \text{K}
\]
where \( r = R / R_s \) and \( \dot{m} = \dot{M} / \dot{M}_{Edd} \). When the accretion rate approaches the Eddington rate, the intermediate disk region becomes dominated by electron-scattering, the spectral function will be of a modified black body and the surface
temperature is higher than given by eq. (10). At still smaller radii, the pressure in the disk is dominated by radiation, rather than by gas pressure, and the thin disk solution becomes thermally unstable. In that inner region the thin disk solution is probably not valid, and has to be replaced by a hot disk solution (e.g. Wandel and Liang 1991). It turns out that the intermediate modified black body region is relatively narrow, and close to the black body - electron scattering boundary the spectrum is nearly a black body one, so both regimes may be approximated by the black body solution.

The spectrum of the black body (and modified black body) disk is given by integrating over the entire disk,

\[ F(\nu) \approx \int_{R_t}^{R_{out}} 2\pi R B_\nu[T(R)]dR \]  

(11)

where \( B_\nu(T) \) is the Planck function and \( R_t \) is the transition radius from the intermediate to the inner radiation-pressure dominated region (for \( \dot{m} < 0.02 \) the black body region extends down to the inner edge of the disk and \( R_t = R_{in} \)).

Since the \( B_\nu(T) \) has a sharp peak at \( h\nu_{\text{max}} \approx 3kT \) and cuts off at higher frequencies, the highest frequency of the black body part of the disk spectrum comes from the radius \( R_t \), with the highest temperature for which the disk is still optically thick. Eq. (11) gives a spectrum which depends on the radial extent of the black body part of the disk. If that part is extended (\( R_{out}/R_t >> 1 \)) the spectrum is almost flat (\( F(\nu) \sim \nu^{1/3} \)) and cuts off beyond \( \nu_{\text{max}} \approx 3kT(R_t)/h \) (or \( 3kT(5R_S)/h \) for \( \dot{m} < 0.1 \). If \( R_{out}/R_t \sim a \) few, the spectrum will be merely a somewhat broadened Planck spectrum.

While in the UV band the thin accretion disk multiple black body spectrum may be a good approximation, the soft X-rays may be produced by a hotter medium due to processes other than black body emission, such as Comptonization, a two-temperature disk (Wandel and Liang 1991) or hot corona (Haardt, Maraschi and Ghisellini 1994; Czerny, Witt and Zycki 1996).

4. Deriving \( M \) and \( \dot{M} \) from the UV spectrum

We want to find an approximate relation between the black hole mass and accretion rate and the continuum spectrum. The accretion rate is determined straightforwardly by the luminosity, via the relation \( L_{\text{ion}} = \epsilon f_{\text{ion}} M \dot{c}^2 \), where \( f_{\text{ion}} \) is the bolometric correction for the ionizing continuum. To estimate the black hole mass we may use the multi-black body accretion disk -spectrum. As discussed in the previous subsection the UV bump cutoff frequency is determined by the highest surface temperature in the black body part of the disk. If the black body region extends down to a radius \( R_t \), and the EUV cutoff energy is \( E_{\text{cuv}} \), then eq. (8) gives (we assume the inner region is optically thin and much hotter, so its contribution in the frequencies of interest can be neglected)

\[ M_8 \approx 1(E_{\text{cuv}}/3eV)^{-2}L_{46}^{1/2}(R_t/R_s)^{-1}. \]  

(12)

In several models the black body regime extends close to the inner disk edge. This is the case in the “\( \beta \)” disk model with viscosity proportional to the gas
pressure ($\nu \sim \beta P_{\text{gas}}$). For low accretion rates ($\dot{m} < 0.1$) this is true also for the “$\alpha$” model with viscosity proportional to the total pressure ($\nu \sim \alpha (P_{\text{gas}} + P_{\text{rad}})$). In this case, since the disk emissivity peaks at $R \approx 5R_S$ (for a non-rotating black hole) we may use eq. 12 with $R/R_s = 5$ in order to find the black hole mass:

$$M_8 \approx \frac{3L_{1450}}{2E_{\text{co}}/3eV}^{1/2}.$$ 

It is possible to do a more refined treatment, calculating for each pair of accretion disk parameters $M$ and $\dot{M}$ fitting not the total luminosity and blue-bump temperature, but the actual observables, e.g. the UV luminosity and spectral index. Wandel and Petrosian (1988) have calculated the accretion disk flux and spectral index at 1450Å, for a grid of accretion disk parameters ($M, \dot{M}$). Inverting the grid they have obtained contours of constant black hole mass and constant Eddington ratio ($\dot{m}$) in the $L - \alpha_{\text{UV}}$ plane (fig 1). Plotting in this plane samples of AGN it is possible to read off the contours the corresponding accretion disk parameters. Comparing several groups of AGN a systematic trend appears: higher redshift and more luminous objects tend to have larger black hole masses and luminosities closer to the Eddington limit (see table 1). Similar results are obtained by Sun and Malkan (1991).

### Table 1. Grouping of AGN accretion disk parameters.

| AGN group       | Log$F_{1450}$ | Log $M/M_\odot$ | $\dot{M}/\dot{M}_{\text{Edd}}$ |
|-----------------|---------------|-----------------|-------------------------------|
| Seyfert galaxies | 28-29.5       | 7.5-8.5         | 0.01-0.5                      |
| Low Z quasars   | 29-30.5       | 8-9             | 0.02-0.1                      |
| Medium Z quasars| 30-31.5       | 8-9.5           | 0.1-0.5                       |
| High Z quasars  | 31-32         | 9-9.5           | 0.03-2                        |
Figure 1. Accretion-disk black hole evolution tracks in the $\alpha - L$ plane (Wandel and Petrosian 1988). Crosses: Seyfert galaxies, triangles, open circles and filled circles: low, medium and high redshift quasars, respectively. Continuous lines: constant mass; dashed lines: constant $\dot{M}/M$ (note that the labeling of the curves in the figure follows the notation $\dot{m} = 16.7\dot{M}/\dot{M}_{Edd}$).

5. Relating the spectrum to the equivalent width

The equivalent width of an emission-line is actually the ratio between the luminosity in the line and the continuum luminosity at the emission-line frequency. The line luminosity is determined by the photoionizing flux, near 1Ryd (13.6 eV). Since $E_{\text{max}} \approx 3kT_{\text{eff}}$ is just below 13.6 eV (see below), this frequency is on the Wien part, and the flux is sensitively influenced by the effective disk temperature, $T_{\text{eff}}$. In the parameter range of interest we may therefore assume that the equivalent width is strongly correlated with $T_{\text{eff}}$. Quantitatively, the correlation is related to the logarithmic derivative

$$\frac{d \ln B_\nu}{d \ln T} = -\frac{xe^x}{e^x - 1}$$

where $x = h\nu/kT$. For $kt < 1$ Ryd, which is true in a wide range of cases, as we show below, eq. (13) gives

$$\frac{d \ln B_\nu}{d \ln T} \approx -h\nu/kT,$$

namely a strong correlation with $T$. 

In order to relate the UV ionizing spectrum near 1Ryd to the accretion parameters, it is necessary to determine the effective black body temperature of the emitting region.

5.1. A general Effective Temperature Estimate

We have already derived a quite general temperature-radius relation for black body emission from an accretion flow (eq. 4). We can apply this relation to determine the temperature or radiation peak energy as a function of the observed luminosity and estimated mass.

In order to determine a characteristic temperature we need either indicate the size of the emitting region (and use eq. 2) or assume an emission model, as done below for the accretion disk model. The size of the emitting region can be bounded by variability analyses. From eqs. 2 and 5 we have

\[ E_{\text{max}} > 10L_{46}^{1/4}(t_{\text{day}})^{-1/2}eV \]  

(14)

If we assume a linear relation between luminosity and variability time, for example, that for objects with a continuum luminosity \( L \sim 10^{46}\) erg/sec the UV variability time is one month, eq. 14 gives

\[ E > 2L_{46}^{-1/4}eV. \]  

(15)

5.2. Effective Temperature Models for an accretion disk

In the framework of the thin accretion disk model, we consider four models for determining the effective temperature.

a. The inner disk black body temperature

When the disk is nearly black body up to the inner edge, we can approximate the spectrum by black body emission near the maximum-emissivity radius, which gives

\[ E_{\text{max}} \approx 3kT_{\text{BB}}(5R_s) = 10(\dot{m}/M_8)^{1/4}eV. \]  

(16)

As discussed in sec. 3 above, this model applies to the “β” disk and to low accretion rates (\( \dot{m} < 0.1 \)) in the α disk.

b. The inner disk radiation-pressure temperature

This model applies to high accretion rates (\( \dot{m} > 0.1 \)) in the α disk, provided the inner disk maintains the temperature profile given by the thin-disk solution. The temperature in the inner, radiation dominated region is given by (Sakura and Sunyaev 1973)

\[ T_{\text{rad}}(r) \approx 2 \times 10^5(\alpha M_8)^{-1/4}r^{-3/8}[1 - (6/r)^{1/2}]^{1/4} K \]  

(17)

Substituting the maximal-emissivity radius \( r = 5 \) gives

\[ E_{\text{max}} \approx 4(\alpha M_8)^{-1/4}eV \]  

(18)

The gas-radiation pressure boundary - taking as \( T_{\text{max}} \) the temperature at the inner boundary between the black body and the radiation-dominated disk

c. The black body -radiation boundary temperature

The effective temperature is taken at the boundary between the intermediate and inner disk regions, at \( r_{\text{mi}} \approx 10(\alpha M_8)^{0.1}\dot{m}^{0.76} \).
The energy of the peak in the spectrum is then derived by substituting \( r_{mi} \) into eq. [17], which gives

\[
E_{\text{max}} \approx 2(\alpha \dot{m} M_8)^{0.3} \text{ eV.} \tag{19}
\]

This model is adequate in the case of a high accretion rate - \( \alpha \) disk when the inner disk does not follow the thin disk model but establishes a stable hot solution (e.g. Wandel and Liang 1991).

**d. The “photospheric” temperature**

In this model we consider as the disk effective temperature the temperature at the radius where the disk becomes effectively optically thin. The effective optical depth in the disk is given by

\[
\tau_* = h \rho (\kappa_{es} \kappa_a)^{1/2},
\]

where \( h \) and \( \rho \) are the disk vertical scale-height and density, respectively, and \( \kappa_{es} \) and \( \kappa_a \) are the electron-scattering and absorption opacities. Equating \( \tau_* \) to unity and eliminating \( T \) and \( r \) by using the temperature profile \( T(r) \) gives

\[
E_{\text{max}} \approx 2\alpha^{-0.4}(\dot{m} M_8)^{-0.26} \text{ eV.} \tag{20}
\]

Note that the last two models give very similar results.

### 6. Evolutionary Scenarios

The evolution of the black hole mass over cosmological times depends on the accretion rate, which may of course change over time. From the accretion disk efficiency and the observed luminosity we can estimate the present accretion rate. In order to determine the black hole evolution, we need to specify the variation of the accretion rate over time. We consider three representative scenarios:

- constant accretion rate
- Eddington limited accretion (constant Eddington ratio)
- spherical accretion from a homogeneous medium

#### 6.1. Constant accretion rate

This would correspond to external feeding of the black hole, which is regulated by an external potential, e.g. by stellar encounters, where the stellar motions are governed by the gravitational potential in the bulge of the host galaxy, far from the influence of the black hole. As the mass of the black hole grows, \( \dot{M} \) does not change, and hence the accretion parameter, \( \dot{m} = \dot{M}/M \sim M^{-1} \). Eventually, accretion rate will become very sub-Eddington, and the black hole will be starved, or at least on a diet. Since \( L \sim \dot{M} \), in this scenario the bolometric luminosity also is also constant. Note that the spectral energy distribution does change (though slowly) as \( \dot{M} \) increases.
6.2. Eddington limited accretion

This would be the case in a black hole that is over-fed. The accretion rate cannot become very super-Eddington, and the source will regulate the accretion rate to $L \approx L_{\text{Edd}}$ or $\dot{m} \approx \epsilon^{-1}$. Since $\dot{m} \sim \dot{M}/M$, $\dot{m} \sim \text{constant}$ implies $\dot{M} \sim M$ and hence $L \sim M$.

6.3. Spherical accretion from a homogeneous medium

In this case we assume the matter supply comes from a homogeneous distribution (gas or stars), due to the gravitational potential of the black hole. On large scales, the accretion will be spherical, and the accretion radius at which the black hole gravitational potential becomes significant is given by

$$R_{\text{acc}} \approx GMv^2 \approx 3M_8^2v_{300}^2 \text{pc},$$

(21)

where $v_{300} = 300v_{300}\text{km/s}$ is the stellar velocity dispersion.

The accretion rate is given by the Bondi formula

$$\dot{M} \approx 4\pi R_{\text{acc}}^2v^2\rho_* = (0.3M_\odot/\text{yr})M_8^2v_{300}^{-3}\left(\frac{\rho_*}{10M_\odot\text{pc}^{-3}}\right),$$

(22)

where $\rho_*$ is the stellar number density.

In this case $L \sim \dot{M} \sim M^2$ and $\dot{m} \sim M$, that is, the Eddington ratio increases with time. Eventually the Eddington ratio will approach unity and the accretion will become Eddington limited.

6.4. Accretion from an inhomogeneous medium

A similar expression can be derived for a non-homogeneous medium, with a density profile $\rho_* \sim R^{-p}$. Assuming the velocity dispersion is independent of $R$, eqs. 21 and 22 give for the accretion rate in that case

$$\dot{M} \sim M^{2-p}.$$  

If also the velocity dispersion has a radial dependence, $v_* \sim R^{-q}$ then we get a more complicated dependence,

$$\dot{M} \sim M^{\frac{2}{1+2q}-q-p}.$$  

(23)

In this case, any functional dependence is possible. If for example $q = 1/4$ and $p = 1/2$, $\dot{M} \sim M^{0.6}$, and if $q = 1/2$ (point mass) and $p = 1/2$, $\dot{M} = \text{const.}$

7. Putting it all together: an evolutionary Baldwin effect?

In the previous section we have found the relation between the accretion parameters $\dot{M}$ and $\dot{m}$, and found the functional dependence of the continuum luminosity on the evolving black hole mass for several accretion scenarios. This enables us to draw evolutionary curves in the $M - \dot{m}$ plane (fig. 1). For example, an Eddington bound accretion disk will evolve along the constant $\dot{m}$ curves (dashed curves in fig. 1). A homogeneously accreting black hole will evolve...
Table 2. The relation between effective accretion disk temperature and black hole mass for various accretion scenarios

| Accretion scenario: | Constant $\dot{M}$ | Constant $L/L_{Edd}$ | Spherical |
|---------------------|--------------------|-----------------------|-----------|
| $L(M) \propto \dot{M}$ | $\dot{M}$ const | $L$ const | $L^{1/2}$ |
| $T_{eff}$ model:    |                    |                       |           |
| $T_{BB}$            | $M^{-1/2}$         | $M^{-1/4}$            | const     |
| $T_{rad}$           | $M^{-1/4}$         | $M^{-1/4}$            | $M^{-1/4}$ |
| $T(\tau_s = 1)$ or $T(BB/rad)$ | const | $M^{-1/4}$            | $M^{-1/2}$ |
| $T(BB-var) \propto L^{-1/4}$ | const | $M^{-1/4}$ | $M^{-1/2}$ |

along curves of $\dot{m} \sim M$, which correspond to nearly horizontal (from left to right) lines in fig. 1, and a constant accretion rate will yield $\dot{m} \sim M^{-1}$ which are almost vertical (upward) lines in fig. 1.

Combining this with the dependence of the effective radiation-temperature on the accretion parameters, and using the result that the emission-line luminosity is positively correlated with the radiation temperature, we can find the relation between the equivalent width and the continuum luminosity for each pair of accretion scenario and temperature model.

7.1. The L-T relation

The dependence of the effective temperature on the black hole mass is summarized in table 2. The header shows the three accretion scenarios and the corresponding dependence of the continuum luminosity on the mass. The next row gives the dependence of the luminosity on the mass for each scenario. The left column shows the temperature models. For each pair the table gives the functional dependence of $T_{eff}$ on $M$. Applying the dependence of $L$ on $M$ it is possible to deduce the dependence of $T$ on $L$.

Combining the black body-radiation boundary and the photospheric models, which have a very similar dependence on the accretion parameters, the table has nine ($T_{eff}, \dot{M}$) pairs, for accretion disk models, and an additional row for the model independent black body-variability estimate of $T_{eff}$ (marked “$T(BB-var)$”).

For all pairs except two (constant $\dot{M}$ with $T(BB-rad)$ and homogeneous medium accretion with $T_{BB}$). The effective disk temperature is decreasing with increasing black hole mass. For all accretion scenarios the optical and UV continuum luminosity is increasing with $M$. This is certainly the case for Ed-
dington bounded accretion and for accretion from a homogeneous medium; For a
countant accretion rate the bolometric luminosity is constant, but as the black
hole mass increases the peak of the accretion disk spectrum moves to lower
frequencies. Since the optical or near UV continuum are on the Rayleigh-Jeans
part of the black body spectrum, the luminosity in these bands increases as the
mass increases even if the total luminosity remains constant.

We note that this is true also for the general temperature-luminosity relation
(eqs. 14 and 15), so the accretion disk model is not essential. In that case
the anti-correlation between temperature and luminosity is built into the the
expression for the temperature, eq. 16.

**Decreasing accretion rate.** In the cases we looked at the accretion rate in-
creases with time or remains constant. What if the accretion rate decreases with
time? In the two latter accretion disk -temperature models (5.2.c and d) we find
$E_{max} \sim M^{-1/3}$, so $T_{eff}$ increases, and so does the line luminosity. If we take
$L \propto \dot{M}$ the continuum luminosity decreases, and there is still a negative cor-
relation. This is the case also in the general L-T relation. For the first two
models (5.2.a,b) the situation is less clear, because $T_{eff}$ in these two models will
decrease (as $\dot{M}^{1/4}/M^{1/2}$ and $M^{-1/4}$, respectively) and also $L \sim \dot{M}$ decreases.
The question whether $T_{eff}$ is correlated or anti correlated with $L$ would depend
on the details of the behavior of the accretion rate.

7.2. **The equivalent width**

How does the equivalent width vary? The equivalent width is defined as $L_{line}/F_{\lambda}$, where $F_{\lambda}$ is the flux per unit wavelength at the wavelength of the line. We have argued that $L_{line}$ depends on the ionizing continuum, which correlates strongly
and steeply with $T_{eff}$. The luminosity in the line is also roughly linearly depend-
ent on the continuum luminosity, $L \sim \lambda F_{\lambda}$, so that

$$L_{line} \propto T_{eff} L,$$

which gives for the equivalent width

$$EW(L) \sim L_{line}/L \sim T(M).$$

The last approximation should not be taken as a linear relation, but rather
as a strong correlation. As shown above, for $3kT < E_{ion} \sim$ few Ryd, $L_{ion}$ is
steeply increasing (and hence strongly correlated) with $T$, and hence $L($line$)$ is
strongly correlated with the temperature.

7.3. **The Exceptions**

We conclude that for many accretion-scenarios and temperature-models (accretion-
disk models or general effective black body related to variabiity) the line lumi-
nosity decreases with increasing mass, except the two for which the effective
temperature is constant, there is an evolutionary Baldwin effect : as the black
hole evolves over cosmological times due to the mass accreted, the continuum
luminosity (optical or near UV) increases, while the equivalent width decreases.
Even the two pairs with a constant effective temperature will eventually show
a Baldwin effect . To see this, note that for the $(T_{BB} - \dot{M}(spherical))$ pair, $\dot{m}$
is increasing as $M$, so it will eventually approach the Eddington accretion rate, and move from the $T_{BB}$ model to one of the other $T_{eff}$ models, which (for $\dot{M}$ (spherical)) do have a Baldwin effect. In the other pair, (constant $\dot{M}$ with $T$(BB − rad)), the situation is opposite, but with the same result: since there $\dot{m} \sim M^{-1}$, eventually the accretion rate will become enough sun-Eddington so that the $T_{BB}$ model will apply, which for the constant accretion rate scenario does have a Baldwin effect.

8. Summary

We suggest that the growth of the central black hole mass due to the accreted matter causes the luminosity and the spectrum to evolve over over the AGN life time. Using general model-independent relations, or the thin accretion disk spectrum, we estimate the evolution of the equivalent width and the continuum spectrum, and show that for plausible evolutionary tracks as well as for the model-independent black body temperature estimate and for most variants of the thin accretion disk model the equivalent width decreases with increasing continuum luminosity implying an evolutionary origin to the Baldwin effect.

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