Line Width and Spectral Index Distributions as Evidence for Axisymmetry in the Broad Line Regions of Active Galaxies

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Abstract. We propose that the scatter in line width versus luminosity of the BLR of AGN arises from a dependence on the line of sight to an axially symmetric BLR. Adopting a simple model for the line width as a function of luminosity and angle, and convolving this with the observed luminosity function, allows us to predict a line width distribution consistent with the available data. Furthermore, we use the relation between the equivalent width of a line and the luminosity in the continuum to predict an observed correlation between line width and equivalent width. The scatter on this correlation is again provided by angular dependence. We also show a viewing angle dependence can produce the X-ray spectral index distribution. The results have applications as diagnostics of models of the broad line region and in cosmology.

1. Introduction

The observed range of FWHM for the broad emission lines in AGN could be driven by various mechanisms. An obvious possibility is the luminosity of the central source. However plots of line width against luminosity for observed samples show no clear correlation between these parameters. It would be natural to expect higher luminosity sources to have higher velocities in the emission regions and thus broader lines, but powerful sources such as 3C273 can have narrower lines than humbler Seyfert galaxies. In the context of ‘unified models’ it is natural to associate this parameter with viewing angle to an axially-symmetric system. In the case of radio-loud sources there is clear evidence of a relation between the radio core to lobe dominance parameter, R, and FWHM (Wills & Browne 1986). The lack of spherical symmetry has been modelled in various ways including a simple Kepler disc, an axisymmetric broad line cloud distribution, and a spherical cloud distribution with non spherical illumination by the central source. The ‘unified model’ may involve a preferred axis of illumination along the axis of symmetry, extending the observed illumination cones of the ENLR into the BLR. Thus, we develop a relation for FWHM dependent on both viewing angle and luminosity. We shall proceed initially in as model-independent a way as possible. Later we shall return to the possibility that we can use the results to discriminate between models.
Since we cannot measure the angle of inclination of the nuclear regions, at least with any certainty, we resort to statistical considerations. If the line width is a function of angle and luminosity then averaging over angle and convolving with the luminosity function will give a line width distribution which can in principle be compared to observations. While the data are not sufficiently extensive to provide a strong test there are several surveys available to validate the general approach.

Our simplest description of the line width dependence contains three parameters which the line width differences in a given source imply are wavelength dependent. However, we can constrain the models further in several ways. We know that the equivalent width of a line is related to luminosity; this is the Baldwin relation. Since the slope of the EW – luminosity relation in a single time-variable nucleus is generally different from the slope of the Baldwin relation this will show some scatter. However, this is small compared to the scatter in the EW–FWHM diagram. Ignoring the scatter in the Baldwin relation we show that the part of the EW–FWHM plot that is populated by sources coincides with that to be expected on the basis of the angle dependence of the FWHM – luminosity relation.

In the context of a unified model with an obscuring torus we would also expect the X-ray continuum slope to be dependent upon viewing angle. This is because the obscuring material preferentially absorbs soft X-rays giving a harder spectrum in sources viewed edge-on. We construct a similar angle-dependent functional form for the dependence of X-ray slope on angle and luminosity and show that this is consistent with the observed distribution of slopes.

We illustrate two applications. First as a diagnostic tool we show that both the dual winds model (Cassidy & Raine 1996) and the disc wind model (Chiang & Murray 1996) have an angular dependence of line width consistent with the observed line width distribution function but that a Keplerian disc does not. The extreme form of the model in which line widths depend on angle only and not on luminosity is ruled out. The line width dependence for the magnetic winds model as shown in figure 6 of Emmering et al. (1992) is not consistent with this model. We have not considered the luminosity dependence of line width in these models but this might provide a more discriminating diagnostic.

Finally we show the preliminary results, but not the details, of a cosmological application to determine the deceleration parameter \( q_0 \) (in principle, given enough data).

### 2. Angular Dependence

We restrict attention to an axisymmetric BLR, so ignoring, for example, warped discs. Line width, \( v \), taken to be a function of viewing angle, \( i \), and luminosity, \( L \), can be written in general as a double series of the form

\[
v(i, L_{44}) = L_{44}^\alpha \sum_{n=0}^{\infty} \sum_{m=0}^{\infty} a_{nm} L_{44}^m \cos n\theta \tag{1}
\]

where \( i = \pi/2 - \theta \) is measured from the axis of symmetry, \( L_{44} \) is the luminosity in units of \( 10^{44} \text{ erg s}^{-1} \) and \( a_{nm} \) and \( \alpha \) are parameters (independent of \( L \) and \( \theta \).
We use only the cosine series to impose symmetry about the equatorial plane. Our model dependence enters only through

(i) the assumption that we can truncate this series, retaining only the terms \(a_{00} = a\), and \(a_{10} = b\). Thus equation (1) simplifies to

\[ v(i, L_{44}) = (a + b \sin i)L_{44}^\alpha, \]

with \(a\), \(b\) and \(\alpha\) constant for a given line.

(ii) We assume also a maximum value for inclination \(i = i^*\). This corresponds to the opening angle of the torus in the unified model. We find that best fits are obtained for \(i^* = 60^\circ\) which, while larger than many estimates of the opening angle, is consistent with more recent observations and also the dual winds model (Cassidy & Raine 1996). For values of \(i < i^*\) we assume systems are randomly oriented.

We obtain a line width distribution by averaging over angle and luminosity. Initially for modelling the line width distribution we use a 2 power-law fit to the B-band luminosity function of Boyle et al. (1988)

\[ \Phi(L_{44}) \propto L_{44}^{-p} \]

\[ p = \begin{cases} 3.85 & \text{for } L_{44} > 2 \\ 1.27 & \text{for } L_{44} < 2 \end{cases} \]  

However, for later work on the X-ray spectral index and cosmology, we will use the X-ray luminosity function of Boyle et al. (1994). The line width distributions can be fitted equally well with the X-ray luminosity function using different values of \(a\), \(b\) and \(\alpha\) which is consistent with predictions that \(L_x \propto L_{\text{opt}}^\beta\) for some value of \(\beta\). The number of systems with line widths between \(v\) and \(v+dv\) is \(N(v)dv\) and is given by

\[ N(v) = \int_{L_{44}} \Phi(L_{44}) \sin i \frac{di}{dv} dL_{44}. \]

This integral is evaluated numerically. Figure [4] shows the results for CIV \(\lambda 1549\) compared to observational samples (Wilkes 1987, Wills et al. 1993 and Brotherston et al. 1994). The Wilkes data is taken from the Parkes flat spectrum survey which is biased towards face-on objects. Thus we expect the peak in the distribution for this sample to lie to the low velocity side of the model. The values of \(a\) (the spherical component of velocity) and \(b\) (essentially the dipole component) are \(a = 2500\, \text{km s}^{-1}\) and \(b = 9500\, \text{km s}^{-1}\) with \(\alpha = 0.15\). We have also obtained fits for MgII \(\lambda 2800\) and H\(\beta\) using data from the RIXOS sample (Puchnarewicz et al. 1997). Because the data is biased it is difficult to assess the agreement with the model statistically, but it seems highly likely that a pure disc model, \((a = 0)\) which would predict a large number of narrow lined systems, and a spherical model \((b = 0)\), which would give a narrow peaked distribution, are ruled out. Rudge and Raine (1998) showed that the angle dependence of line widths in both the disc winds model of Cassidy & Raine (1996) and the disc wind model of Chiang and Murray (1996) can be fitted to the form (2).

The Baldwin relation for the line equivalent width, \(EW\), is

\[ EW \propto L^\beta \]
Figure 1. Model predictions for C iv line width distribution overlaid with observed data by Wilkes (1987) (left) and Wills et al. (1993) (dashed) and Brotherton et al. (1994) (dot-dashed).

Figure 2. FWHM – EW plot for C iv.

where for these lines $\beta_{\text{C IV}} = -0.17$ (Peterson, 1997), $\beta_{\text{H\beta}} = 0.4$ and $\beta_{\text{Mg II}} = -0.37$ (Puchnarewicz, unpublished). We have $v_{\text{FWHM}} \propto L^\alpha$ with a large scatter from the angular dependence. We therefore predict that

$$EW \propto v_{\text{FWHM}}^{\beta/\alpha}$$

with a large scatter. We construct a log $EW$ – log $v_{\text{FWHM}}$ plot for systems drawn at random from a population given by the luminosity function (equation 3) and uniformly distributed in angle in the range $0 < i < i_*$. This is shown in figure 2 (see figure 7 of Wills et al. (1993) for comparison with observations). We would expect the time dependence of the Baldwin relation (and possibly a gradual rather than a sudden cut-off near $i \sim i_*$) to smooth out the upper edge of the predicted distribution. The predicted slope of the upper boundary is $\beta/\alpha = -1.1$ compared with $-1 \pm 0.25$ from inspection of Wills et al. (1993). Similar plots can be obtained for MgII and H\beta with slopes 1.1 and 1.3 respectively, compared with $1.6 \pm 0.4$ and $0.6 \pm 0.4$ (Puchnarewicz, unpublished).

3. X-ray Slopes

We now apply a similar idea to the slope, $\alpha_x$, of the X-ray spectra. The analytical form we choose is motivated by the following argument. Assume that the hard
X-ray luminosity $L_h$ at $\nu_h$ is independent of angle and the soft component $L_s$ centered on $\nu_s$ has the form (3). Then

$$\alpha_x = \frac{\log(L_s/L_h)}{\log(\nu_h/\nu_s)} \propto \log[(c + d \sin i)L_{44}^\beta]$$

(with $d < 0$ to accommodate softer spectra in face-on systems). As above we can derive the corresponding $\alpha_x$ distribution by integrating over the luminosity distribution and angle. In figure 4 we show the theoretical curve for $c = 4.0$, $d = -3.0$ and $\beta = -0.8$, overlaid on the spectral index distribution for the RIXOS (Puchnarewicz et al. 1997), EMSS (Ciliegi & Maccacaro 1996) and Wandel & Boller (1998) objects. It can be seen that the Wandel & Boller objects are not fitted by the model curve. This is due to the sample having a large number of NLS1’s which have in general a softer X-ray spectrum. Combining equations (3) and (4) we obtain an expression for line width dependent upon spectral index and luminosity. This obviously predicts that face-on sources with narrower lines also have softer X-ray spectra, as is shown in Wandel & Boller (1998). However their spherically symmetric BLR, which models this relation, does not reproduce the observed line width distribution (Rudge & Raine in prep.).

4. Application to Cosmology

Since the analysis enables us to account for the scatter in the FWHM-luminosity relation for AGN it should be possible in principle to use the model as a cosmological test. To indicate the results that might be expected we show the difference in evolution of $N(\nu)$ from $z < 0.5$ to $2.5 < z < 3.0$ for $q_0 = 0.5$ and $q_0 = 0$, ($H_0 = 50$ km s$^{-1}$Mpc$^{-1}$). Of course, for practical application the test requires a large sample of line widths at high redshift.

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Figure 4. Line width distribution for $0 < z < 0.5$ (left) and $2.5 < z < 3$ (right). Solid line is for $q_0 = 0.5$ and dashed line is for $q_0 = 0$. Model parameters $a$, $b$ and $\alpha$ are the same in all cases.

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Discussion

Mark Bottorff: For the magnetic winds model (Emmering et al. 1992) the figure shown in their paper is a very specific case. Changing the input parameters, particularly the initial angle of the clouds relative to the accretion disc surface, can produce a $v–i$ relation in the opposite sense to that shown i.e. consistent with this model.
Christopher Rudge: A deeper investigation of this model could produce more detailed information on the exact nature of the $v$–$i$ relation. While changing the initial conditions of the clouds will obviously affect the $v$–$i$ relation it is unclear how much variation is possible whilst still producing reasonable emission line profiles. Consideration should also be given to the ability of this model to predict the EW–FWHM relation in the case of $v$ decreasing with increasing $i$.

Michael Corbin: The evidence for viewing angle effect based on the R parameter can only be applied to radio loud objects. The line width distributions for radio loud and radio quiet objects are significantly different in my sample (Corbin 1997), even with the same magnitude limit, indicating an intrinsic difference between radio types.

Christopher Rudge: The FWHM–R relation is perhaps one of the better pieces of evidence for a viewing angle effect but not the only piece of evidence i.e. relation to spectral index. The observed sample given in Corbin (1997) does show a small difference between the line width distributions for the radio loud and radio quiet objects. However even in the magnitude limited case, the luminosities of the radio loud objects are slightly higher than for the radio quiets. This model predicts that the distribution would therefore peak at a higher FWHM for the radio loud objects.

Neil Brandt: Were the spectral index model and the $\alpha_X$–$v$ relation developed specifically to model the RIXOS objects or to investigate, more generally, the Boroson and Green eigenvector? Note also that the intrinsic absorption seen in the RIXOS sample was not observed in our sample of NLS1’s.

Christopher Rudge: While the spectral index model was initially suggested by the study of the RIXOS objects by Puchnarewicz et al., we have also been able to fit other samples with this model. Future work is expected to include a study of the various parameters related to the Boroson and Green eigenvector. There is some evidence that the NLS1’s are predominantly face on Seyfert 1’s. If this is the case then our model would correctly predict their narrow lines and the lack of observed dust absorption.