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A Look at What Is (and Isn't) Known About Quasar Broad Line Regions and How Narrow-Line Seyfert 1 Galaxies Fit In

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Abstract

The evidence is reviewed that the Broad Line Region (BLR) probably has two distinct components located at about the same distance from the central black hole. One component, BLR II, is optically-thick, low-ionization emission at least some of which arises from a disc and the other, BLR I, is probably optically-thin emission from a more spherically symmetric halo or atmosphere. The high Fe II/H β ratios seen in Narrow-Line Seyfert 1 galaxies (NLS1s) are not due to strong Fe II emission, as is commonly thought, but to unusually weak Balmer emission, probably caused by higher densities. NLS1s probably differ from non-NLS1s because of the higher density of gas near the black hole. This produces a higher accretion rate, a denser BLR, and a view of the central regions that is more face-on.

Key words: galaxies: active; galaxies: Seyfert; quasars: general; quasars: emission lines

1 Introduction

I was asked by the organizers if I would give “some kind of review of the properties of the BLR.” Why, at a workshop on NLS1s, should we consider BLRs in non-NLS1s? For me, and perhaps most people who attended this workshop, the interest of NLS1s has been that these extrema in the distributions of AGN properties might tell us more about how *all* AGNs work. This is, however, a two-way street: if NLS1 are “just” extrema of a continuum of BLR properties, then NLS1 BLRs are not *fundamentally* different from the BLRs of other AGNs. Therefore, a model of NLS1s *must have the BLRs be consistent with those of non-NLS1s*. I present here an overview of some general BLR results with which NLS1 models need to be consistent.

In BLR research the big question is “what role does the BLR play in the quasar phenomenon?” Some very basic specific questions include:

- Is the BLR one thing or more than one thing?
- Where is the BLR located? Or where are the components of the BLR located? (*e.g.*, what is the distribution in R, Θ, Φ ?)
- Where is the BLR coming from or going to?

A survey of participants in the 1998 Nebraska BLR conference revealed a complete lack of consensus on the answers to these basic questions (Gaskell 1999).

2 Basic BLR Parameters

Observationally an AGN presents the astronomer with the four Stokes parameters as a function of projected velocity (v_{proj}) and time (t). If we ignore polarization and subtract out various problems such as the continuum, absorption lines, and blended emission lines, then, for each line, i , we get $L_i(v_{\text{proj}}, t)$. If we ignore t we get $L_i(v_{\text{proj}})$, the line profiles. If we ignore v we get L_i , the integrated intensities of the lines.

The traditional approach (going back to the late 1960s) has been to try to explain L_i with a “typical” photoionized cloud. Obviously this assumes that the profiles are the same. We will see below that they are not, but this traditional approach has none the less been quite successful in explaining the stronger high-ionization lines and has produced a number of important results.

- The broad lines are produced mainly by *photoionization*. We can say this with confidence because *the lines vary with the continuum*, and the lines can vary in intensity by an order of magnitude. Not only do the high-ionization lines vary with the continuum, but the low ionization lines (such as Mg II and Fe II) do too. Other energy input sources might be present, but the dominant energy input is from photoionization.
- The mean physical conditions in the BLR do not vary a lot from object to object.
- The covering factor, $\Omega \sim 10\%$.
- The density is $\sim 10^{10}$ – 10^{12} (or 10^{13}) cm^{-3} .
- The mass of gas seen in the BLR is of the order of a solar mass.
- If the BLR emission arises in free clouds with dimensions comparable the the Strömgen length, the number of clouds is enormous ($\sim 10^{16}$)
- Abundances are \sim solar to a few times solar (*e.g.*, Gaskell, Wampler, & Shields 1981; Hamann & Ferland 1993) which is consistent with what one expects in the centers of galaxies.

3 Optical Fe II Strengths in NLS1s

One of the major challenges for photo-ionization models has always been to explain the great strengths of low-ionization lines. In particular, explaining the origin of Fe II emission is a long-standing problem. This is reviewed by Suzy Collin-Souffrin elsewhere in this volume so I will not discuss it here, but I will point out one result (Gaskell 1985) which is not widely appreciated in discussion of the BLR of NLS1s.

One supposed characteristic of NLS1s is the great strength of the optical Fe II emission (*e.g.*, Boller, Brandt, & Fink 1996). Wills (1982) pointed out for a heterogenous collection of AGNs that Fe II/H β seemed to be roughly inversely proportional to the FWHM. As is well known, optical Fe II is hard to measure. I therefore looked at H β and optical Fe II emission in the Lick Observatory sample of Seyfert 1 spectra of Osterbrock and his graduate students – a sample with very high signal-to-noise ratio spectra where the lines had been carefully de-blended. From this homogeneous sample I was able to confirm the FWHM *vs.* Fe II/H β correlation of Wills (1982). However, the interesting thing is that while there is considerable object-to-object variation in the equivalent width of the optical Fe II (something that needs to be explained), *there is no correlation of the equivalent width of the Fe II emission with FWHM* (see figure 2 of Gaskell 1985). Instead, the FWHM *vs.* Fe II/H β correlation arises *because H β gets weaker as the lines get narrower*. So rather than trying to explain a (non-existent) anomalous strength of Fe II in NLS1s, we should be trying to explain the anomalous weakness of H β in NLS1s. H β is probably being thermalized because of the high density and this led to the prediction (Gaskell 1985) that UV spectra of narrow-line objects would show an increase in the strength of Si III] relative to C III]. This prediction has now been confirmed (Kuraszkiewicz *et al.* 1998; Wills *et al.* 1999).

4 The Need For (At Least) Two BLR Components

To be valid the traditional “typical photoionized cloud” analysis requires the $L_i(v)$ to be the same. If we look at the first moments of the line profiles (the line centroids) we find that the high-ionization lines are blueshifted relative to both the low-ionization lines and the rest frame of the host galaxy (Gaskell 1982). If we look at the second moments of the line profiles (the line widths) we find that FWHM \sim ionization potential (Shuder 1982). These differences and other considerations have led some workers to argue that there are at least two fundamentally different BLR components (Gaskell 1987; Collin-Souffrin & Lasota 1988). Using the terminology of Gaskell (1987) these are:

- **BLR I**—a fairly traditional H II region producing the strong UV lines (*e.g.*, as in the models of Davidson 1973). Collin-Souffrin & Lasota (1988) refer to BLR I as the “HIL” (high-ionization) BLR.
- **BLR II**—a large partially ionized zone (PIZ) which produces strong Balmer emission, Mg II, Fe II, Ca II, O I, *etc.*. Collin-Souffrin & Lasota (1988) refer to this as the “LIL” (low-ionization) BLR.

There are several reasons why I believe we need two (or more) components:

1. *To Explain the Integrated Intensities*

Collin-Souffrin *et al.* (1979, 1980, 1981) have argued that single photo-ionized clouds are unable to simultaneously explain the integrated line intensities of both the high-ionization lines and the hydrogen lines (especially Ly α /H β). This is true *a fortiori* when one considers $L_i(v)$ (Snedden & Gaskell 1999*ab*, 2000). By constructing a grid of models using Gary Ferland’s photoionization code CLOUDY (Ferland 2000) and looking at the profiles of the strong BLR I lines, we get a hydrogen density $n_H \sim \text{const.}$ ($\sim 10^{11} \text{ cm}^{-3}$), independent of the projected velocity, v , and an ionization parameter, $U_1 \sim \text{const.}$ ($\sim 10^{-1.5}$), again independent of v . We found that the BLR I lines alone can be explained by either optically thick or optically thin models.

When we take the physical conditions we deduce from our analysis of the BLR I lines and try to predict the strengths of the BLR II lines we find that optically thick photoionization models can only explain the hydrogen-line ratios at low v ; the *wings* of the Balmer lines are seriously overpredicted (see Figure 2 in Gaskell & Snedden 1999*a*). This means that BLR I *is mostly optically thin*. This has been already suggested by Ferland, Korista, & Peterson (1990) from emission-line variability considerations. When we try to use our grids of CLOUDY models to deduce conditions from the BLR II lines alone we find we need very optically thick clouds with $n_H \sim 10^{13} \text{ cm}^{-3}$ and a very low ionization parameter, $U_1 \sim 10^{-3} - 10^{-4}$ to satisfy the constraints (Snedden & Gaskell 2000).

2. *To Explain the Different Line Profiles*

(a) As already noted above, BLR I lines are broader than BLR II lines.

(b) Not only are the line widths different, but Mathews & Wampler (1985) found the C IV (BLR I) and Mg II (BLR II) FWHMs in general to be uncorrelated for both radio-loud and radio-quiet AGNs. Further analysis (Gaskell & Mariupolskaya 2000), while confirming the independence of the C IV and Mg II FWHMs, shows that the relationship between BLR I and BLR II FWHMs is complicated (for example, Corbin 1993 found the FWHMs of C IV and H β to be quite well correlated).

3. *Because BLR I is Blueshifted*

The standard explanation of the blueshifting (Gaskell 1982) is that BLR I is (at least approximately) spherical and radially outflowing but something (the accretion disc or inner torus) is blocking our view of the far side. There are, however, problems with this and other explanations have been offered (see below).

4. *Because BLR I and BLR II Emission Come From Different Radii*

One of the first results of what is often called “reverberation mapping” of BLRs (using light echoes to probe the structure of BLRs) was that the higher-ionization lines come from closer in to the central source (Gaskell & Sparke 1986). This has now been widely confirmed by major observational campaigns studying a number of objects. Not only are the responsivity weighted radii different, but the “transfer functions” (the light echoes seen in response to a δ -function in the photoionizing continuum) of BLR I and BLR II have difference shapes (compare Krolik *et al.* 1991 with Horne, Welsh, & Peterson 1991). While we now recognize that BLR I is “stratified” and seems to have a different structure from BLR II, it is important to note that the distances of the different emitting regions from the black hole are not very different.

5 Spectropolarimetric Results

Spectropolarimetry is proving to be a powerful tool for probing the structure of AGNs. Three results stand out in particular:

- (1) The percentage polarization can be different for the BLR and the continuum.
- (2) The position angle (PA) of the polarization can also be different for the BLR and the continuum.
- (3) Both the percentage polarization and the PA can vary *across* the BLR line profiles (see, for example, Martel 1998).

The first two results imply that the size of the scattering region is comparable to the size of the BLR (and perhaps the scatterer is mixed in with the BLR?). The third result is very important for BLR kinematics because it implies that *there is organized bulk motion in the BLR*.

6 How is the BLR Gas Moving?

There is no consensus as to what the BLR is doing. Almost every kind of model of BLR kinematics is still under active consideration: random motions, Keplerian discs, infall, and various sorts of outflows or winds. I believe that understanding BLR kinematics is crucial for understanding the role of the BLR in AGNs and why NLS1s are different. My confident pre-1987 expectation was that BLR I at least was moving radially outwards. This was because of

- The blueshift of BLR I.
- The existence of broad absorption line quasars. Gas causing blueshifted absorption lines must be moving away from the quasar.

If the BLR is moving radially outwards then as the emission lines vary in response to changes in the ionizing continuum we expect the blue wings of the line to vary first, since this gas would be closest to our line of sight. I was therefore quite surprised to find (Gaskell 1988*b*) that the wings of C IV vary almost together and the red wing leads the blue wing *slightly*. This has now been confirmed for many objects (see, for example, Koratkar & Gaskell 1991). There are several possible solutions to the dilemma these results present:

1. *The Shifts Are Not Caused by Bulk Radial Motion of BLR Clouds*

Electron scattering can cause a blueshift of line profiles (Edmonds 1950). This has been modeled more recently by Kallman & Krolik (1986) and Ferrara & Pietrini (1993). At least a modest optical depth to electron scattering is needed ($\tau_{es} \sim 0.5$). This mechanism has the advantage that we *know* the electrons are there because we see them in polarized light as the so-called “mirrors” in some Seyfert 2s. Continuity requires that the density of electrons increase inwards from the observed “mirror” to the BLR as r^{-2} . The stellar wind model of Taylor (1998; see also these proceedings) offers another possible explanation of the blueshifting.

2. *There is Bulk Radial Outflow, but it is Not Causing the Blue Wing to Vary First*

There have been a couple of proposals in this category. These include the disc/wind model of Chiang & Murray (1996) and the hydromagnetic outflow model of Bottorff *et al.* (1999).

7 Line Emission from Discs

If the dominant motion of the BLR is in a plane, the line width depends on the orientation of the plane of motion (*e.g.*, the disc) to the observer's line of sight. A face-on viewing position has been a widely discussed explanation of the narrowness of the BLR lines in NLS1s. Wills & Browne (1986) showed that, for radio-loud AGNs at least, there is indeed a strong correlation between the FWHM of $H\beta$ and orientation.

If we are not viewing the disc face on, the Keplerian rotation will make us see double-humped profiles. Such displaced humps have long been seen, especially in the so-called '3C 390.3 objects,' but the disc explanation of this line profile structure has been controversial (see Gaskell & Snedden 1999 and Sulentic *et al.* 1999). Problems arise because the disc model makes some definite predictions that were not verified:

- The blueshifted hump should always be stronger than the redshifted hump. In fact it has long been known that there are cases where the *redshifted* hump is much stronger than the blueshifted hump (*e.g.*, Osterbrock & Cohen 1979) and our statistical study of line profiles (Gaskell & Snedden 1999) shows that red peaks are about equally likely to be stronger than blue peaks.
- The BLR responds to changes in the photoionizing continuum. If the source of ionizing radiation is located on the axis of symmetry, the observer sees the red and the blue sides of the line going up and down in intensity together. Gaskell (1988a) pointed out that this was not the case.

Despite my earlier objections I have now become convinced that we *are* seeing the signature of disc emission in some BLR line profiles. The *International AGN Watch* (IAW) monitoring of 3C 390.3 (Dietrich *et al.* 1998) showed that on a *light-crossing timescale* both the red and blue sides of the Balmer lines vary up and down together as predicted by the disc model. The profile changes reported earlier were on a much longer timescale and are not related to ionizing continuum changes. Interestingly, profile changes in typical (non-NLS1) radio-quiet AGNs are also independent of what the ionizing continuum is doing (see Peterson, Pogge, & Wanders 1999).

The line-profile statistics and long-term profile variability observations can all be explained if there is emission from a disc that is not azimuthally symmetric. The asymmetries might be hot spots or spiral wave patterns on the disc (see Gilbert *et al.* 1999 for some possible models). In at least one object (3C 390.3), a drift in wavelength consistent with orbital motion has been seen (Gaskell 1996; Eracleous *et al.* 1997).

It might be said that NLS1s are very different from broad-line radio galaxies, such as 3C 390.3, but it is important to recognize that some objects dis-

playing disc-like emission line profiles are radio-quiet Seyfert galaxies. Also, difference spectra of “typical” Seyferts often show the same disc-like signatures seen in 3C 390.3 objects. We have carried out a study of the statistics of apparent structure in Balmer line profiles for samples of radio-loud and radio-quiet objects (Gaskell & Snedden 1999), and the results are consistent with the hypothesis that a disc-like component of BLR emission is present in *all* AGNs, regardless of type. Disc-like profiles are harder to detect in narrower-line objects whether they be radio-loud or radio-quiet. We believe the disc component is harder to detect in radio-quiet objects simply because they tend to have narrower line profiles.

8 Putting it All Together

There are many results and complications that space does not permit me to cover, but, while the jury is still out on many key issues (notably the kinematics), I think a picture is emerging: the BLR consists of two main components. One component (BLR II) arises predominantly in a very optically thick disc and the other (BLR I) arises predominantly from a more spherical distribution of more optically thin gas. If this is correct the leading model is therefore one of the disc-plus-atmosphere models proposed by Shields (1977), Collin-Souffrin *et al.* (1980), and others.

At a conference like this we are focusing in on differences between objects but it is important to realize the great *similarities* between members of the quasar family, especially in continuum and BLR properties. The differences are mostly subtle, and it took a lot of work by many people over many years to discover them. There is also a continuum in the distribution of differences.

Why do BLR properties change as the BLR II lines get narrower? (*i.e.*, as we go to NLS1s)? The thermalization of H β and the increase in Si III]/C III] tells us that the density must be higher in NLS1s. Since the FWHM difference is most pronounced for the BLR II lines, and variations in the FWHM of BLR II are demonstrably influenced by orientation for non-NLS1s (Wills & Browne 1986), NLS1s are presumably seen face-on. I offer the following as a tentative attempt at an integrated picture of the NLS1 phenomenon:

- (1) The driving factor is a denser circumnuclear environment.
- (2) This denser environment provides an enhanced black hole fueling rate, as has been argued elsewhere in this conference.
- (3) The denser environment produces more obscuration of the central engine and produces a narrower opening angle through which we see BLR II more face-on than in non-NLS1s.

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