Mem. S.A.It. Vol. 79, 1090
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Structure and kinematics of the broad-line region and torus of Active Galactic Nuclei

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Abstract. Energetics considerations imply that the broad-line region (BLR) has a high covering factor. The absence of absorption from the BLR means that the BLR has to have a flattened distribution and be seen through a polar hole. The BLR is the inward extension of the torus and they have similar geometries and covering factors. Reconciling velocity-resolved reverberation mapping, spectropolarimetry, and the increasing blueshifting of BLR lines with decreasing distance from the centre, implies that the BLR has a significant inflow component. This inflow provides the mass inflow rate needed to power the AGN. We suggest that the mechanism producing the outward transport of angular momentum necessary for the net inflow of the BLR is the magneto-rotational instability, and that the BLR and outer accretion disc are one and the same.

Key words. accretion: accretion disk — black hole physics — galaxies:active — galaxies:quasars:emission lines — scattering

1. Introduction

Even though active galactic nuclei (AGNs) are too far away and their inner regions too small to resolve, many cartoons of suggested AGN structures have nevertheless been published over the last four decades or so. A *Google Images* internet search found cartoons suggesting a very wide variety of possible structures.[1] This lack of a consensus is significant because it can be argued that if we don't know what something *looks* like, then we don't really understand it.

Our best probe of the inner workings of AGNs is provided by the broad-line region (BLR), but, unfortunately, one of the areas in which cartoons of AGNs differ most is in the location and structure of the BLR. It is most commonly thought of as having a spherical or quasi-spherical distribution, but it is also depicted as being between the accretion disc and the torus, just above the accretion disc, or in cones around the radio jets. Closely related to the question of where the BLR gas is located is the question of how the BLR gas is *moving*. Knowing the answers to these two fundamental questions is crucial for understanding what

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[1] The only point they were unanimous on was that the black hole was always in the centre!

the BLR is and for using it to determine black hole masses. For example, starting with Dibai (1981), for a given observed BLR line width, v, and optical luminosity, L_{opt}, the quantity $v^2 L_{opt}^{1/2}$ has been used to estimate black holes masses, but for such mass estimates to be reliable we need to know both the distribution of the BLR gas, and what is controlling the gas motions.[2]

In this paper we briefly discuss our recent results on the structure and kinematics of the BLR. Further details can be found in Gaskell, Klimek, & Nazarova (2008)(= GKN) and Gaskell & Goosmann (2008).

2. The structure of the broad-line region

2.1. The BLR is flattened

If the spectral energy distribution of an ionizing continuum source and the covering factor of the surrounding gas are known, the equivalent widths of emission lines can be calculated from the conservation of energy (Stoy 1933). MacAlpine (1981) pointed out that the equivalent width of the He II line in AGNs implied a very BLR high covering factor. In fact, based on the extrapolation of reported UV continua shapes of the time, the covering factor, $\Omega/4\pi$, needed seemed to be much greater than 100%. This problem has been referred to as "the energy-budget problem" (see MacAlpine 2003 for a recent review). Even a covering factor of 100% is too high because unambiguous Lyman continuum absorption edges at $\lambda 912$ due to the BLR are *never* seen (see Koratkar & Blaes 1999 for a review). If, as is widely assumed, the BLR is spherically symmetric, the limits on Lyman limit absorption put the BLR covering factor at only a few percent at most, which is far too low to explain the observed equivalent widths of of BLR lines.

NGC 5548 probably has the best studied BLR and continuum of any AGN because it has been the target of intensive multi-wavelength monitoring campaigns by the *International AGN Watch* (*IAW*; e.g., Clavel et al. 1991, Peterson et al. 1991, Peterson et al. 1992, Korista et al. 1995) and other groups over the past two decades. Gaskell, Klimek, & Nazarova (2008) therefore chose NGC 5548 for a detailed analysis of BLR energetics.

MacAlpine (1981) suggested that reddening could be a solution to the energy-budget problem. However, Gaskell et al. (2004), Czerny et al. (2004), and Gaskell & Benker (2008) have found that most AGNs have relatively flat reddening curves, and the reddening curve Gaskell, Klimek, & Nazarova (2008) find for NGC 5548 is consistent with the mean AGN reddening curve of Gaskell & Benker (2008). Dereddening by this curve lowers the covering factor a little, but still leaves it around $\sim 40\%$ for lines of a wide variety of ionization.

Since variability leaves no doubt that BLR emission is driven by photoionization, and the spectral energy distribution is fairly well constrained, GKN argue that the combination of the high covering factor needed to explain the BLR line strength, and the lack of Lyman limit BLR absorption require that the BLR *cannot* be spherically symmetric. Instead *we have to always be viewing the BLR through a hole.* This has important consequences.

2.2. The BLR is self-shielding

The current standard model of the BLR has random clouds each with a clear line of sight to the central ionizing source. A typical optically-thick cloud will produce high-ionization lines from its front side and low-ionization lines from its back side. Each cloud will thus produce lines through the full range of ionization, although the ratios will change somewhat with the distance from the ionizing source. A random mix of such clouds (the so-called "LOC" model of Baldwin et al. 1995) naturally reproduces the integrated BLR spectrum.

However, because of the high covering factor ($\sim 40\%$) and the requirement of a flattened BLR, *there is 100% covering in the equatorial plane*. Thus the more distant clouds do *not* have a clear line of sight to the central ionizing source. Instead, clouds will self shield each other so that the radiation reaching the outer

[2] One cannot, for example, get the mass of the sun by measuring the speed of the solar wind!

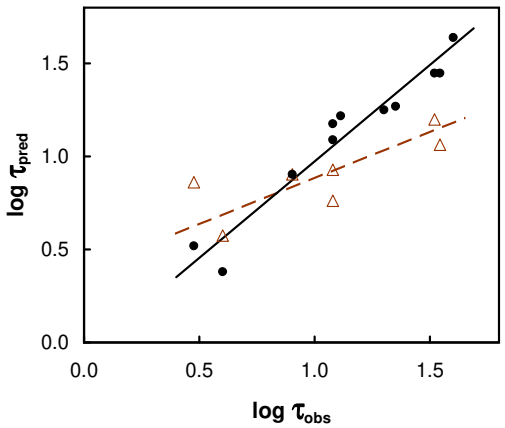

Fig. 1. Observed BLR reverberation mapping lags for different ions in NGC 5548 versus the predicted lags from the exposed cloud LOC model (brown triangles), and the self-shielding model of Gaskell, Klimek, & Nazarova (2008). The lines are OLS-bisector fits.

BLR clouds will have been absorbed by going through the inner BLR. This means that the more distant clouds behave like the back sides of exposed clouds in the standard model, and the range in ionization seen in a single cloud is now spread out across the whole BLR. Such a self-shielding BLR was explored by MacAlpine (1972).

It has long been recognized that higher-ionization lines arise closer in to the centre of an AGN on average (Gaskell & Sparke 1986; Clavel et al. 1991). The GKN model predicts a wider range of effective radii than the standard model because in the GKN model different clouds emit different lines, while an exposed cloud LOC-type model predicts a narrower range of radii because every cloud emits every line. Fig. 1 shows the predictions of the two models versus measured lags from the *IAW* monitoring of NGC 5548. As can be seen, the self-shielding GKN model is a significantly better fit.

2.3. The BLR is the inner extension of the torus

The BLR shields not only its own outer regions but also the torus, and this needs to be allowed for when considering torus energetics. Shielding means that (a) the torus has to have a larger covering factor in order to reprocess less energy, and (b) the dust can survive closer to the black hole because it receives less energy. After allowance for the shielding, the torus opening angle Gaskell, Klimek, & Nazarova (2008) find for NGC 5548 is similar to the torus opening angles estimated from the fraction of type-1/type-2 AGNs of comparable luminosity

We believe that the BLR and torus covering factors are similar for other AGNs in general. If the BLR has a larger covering factor, then as we approach edge-on viewing, the BLR would start to block the continuum before the torus did, yet, as noted above, we never see BLR absorption. When we do see line absorption (in broad-absorption-line quasars) it is always blueshifted and is therefore part of a high-velocity outflow. For thin tori seen near edge-on we could also see strong BLR lines without seeing the AGN continuum directly, and this also is never observed. Conversely, the torus covering factor cannot be greater than the BLR covering factor close in because the dust cannot survive there in the direct radiation field of the AGN.

Netzer & Laor (1993) proposed that the outer boundary of the BLR is set by dust formation and this is confirmed by IR reverberation mapping (Suganuma et al. 2006). The BLR thus starts where the torus stops, and, for the reasons just explained, they will have similar covering factors at this point. We therefore believe that *the torus and BLR are part of the same thing*. For additional discussion of this, see the contributions by Moshe Elitzur and Hagai Netzer in these proceedings.

3. The kinematics of the broad-line region

Chaotic virialized motions, Keplerian orbits, radiatively-driven outflows, infall, and various combinations of these possibilities, have all been extensively considered for BLR motions. The dominant early view was radial outflow. Radiation pressure accelerated lines could produce the observed profiles

(Blumenthal & Mathews 1975), blueshifted intrinsic absorption lines prove that at least some gas is outflowing, and the discovery of the blueshifting of the high-ionization BLR lines (Gaskell 1982) has been widely taken as evidence of the outflow of the high-ionization BLR gas.

Unfortunately, velocity-resolved reverberation mapping (Gaskell 1988) gave the conflicting result that the BLR was *not* outflowing but gravitationally bound instead. Because this makes the current AGN black hole mass estimating industry possible this is now a very popular idea. However, the conflict with the evidence for outflow, especially the blueshifting of the high-ionization lines, has remained a major problem. The most widely adopted solution has been to assume that the BLR has *two* components (see Gaskell 2000 for a review) with different kinematics: a gravitationally-bound, low-ionization BLR, and a radially-outflowing, high-ionization BLR. These two components have often been associated with "disk" and "wind" components. Unfortunately, as Gaskell & Goosmann (2008) point out, the first velocity-resolved reverberation mapping showing no outflow was of the *high*-ionization C IV line.

Gaskell & Goosmann (2008) show that the blueshifting can be produced from electron scattering from an inflowing medium. There are a couple of independent lines of evidence pointing to a net inflowing component of the BLR velocity. Firstly, velocity-resolved reverberation mapping studies have *repeatedly* shown that there is an *infalling* component to the velocity (Koratkar & Gaskell 1989; Crenshaw & Blackwell 1990; Koratkar & Gaskell 1991a,b; Korista et al. 1995; Done & Krolik 1996; Welsh et al. 2007). While this might be a marginal result for just one line in one AGN, the overall significance for the entire sample considered in the studies is substantial. The second line of evidence for infall comes from high-resolution spectropolarimetry: the systematic change in polarization as a function of velocity across the Balmer lines requires a net inflow of a scattering region exterior to the Balmer lines (Smith et al. 2004). On the basis of these reverberation mapping and spectropolarimetric results, Gaskell & Goosmann (2008) adopt net infall velocities of $\sim$ 1000 km s^{-1} (about a quarter of the FWHM of a typical BLR line), and show, using the Monte Carlo radiative transfer code *STOKES* (Goosmann & Gaskell 2007), that electron scattering off infalling material produces the blueshifting of the high-ionization lines. Polarization reverberation mapping (Gaskell et al. 2008a) shows that there is significant scattering at the radius of the BLR. As we illustrate in Fig. 2, a range of optical depths and geometries for the infalling scatterers readily reproduces the observed high-ionization line profile. The model also reproduces the dependence of the blueshifting on the ionization of the line.

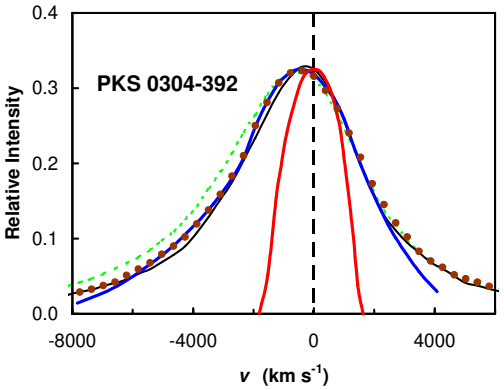

Fig. 2. The profiles of O I λ1305 (narrow symmetric profile shown in red) and C IV λ1549 (thick blue line) for the quasar PKS 0304-392. The thin black line is the blueshifted profile produced by a spherical distribution of scatters with τ = 0.5, and the dashed green line is the profile produced by the same distribution with τ = 1. The brown dots are the profile produced by an infalling cylindrical distribution of scatterers with τ = 20 and a half opening angle of 45 deg. PKS 0304-392 observations from Wilkes (1984)

4. Discussion

4.1. The overall picture

Our overall picture of an AGN is summarized in our own AGN cartoon shown in Fig. 3. Material from the torus has a net inflow. As

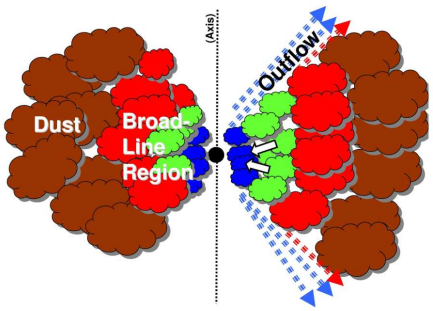

Fig. 3. A cartoon showing a cross section of an AGN through the rotation axis.

it spirals in, the dust sublimates and we have a dust-free BLR. Because the BLR and torus are physically thick there must be a vertical "turbulent" component of motion, v_{turb} (see Osterbrock 1978). At any given radius the relationship between the various velocity components is

$$v_{Kep} > v_{turb} > v_{inflow} \approx 0.25 v_{Kep} \quad (1)$$

where v_{Kep} is the Keplerian orbital velocity.

To complete the picture, there is a higher velocity, low-density outflow in the polar cones which is indicated by the dotted arrows in Fig. 3 and is discussed elsewhere in these proceedings. If we animate our cartoon then in a co-rotating reference frame we would see turbulent motions of the BLR with a slower net infall (the white arrows in Fig. 3).

4.2. The mass inflow rate

Since we have estimates of the inflow velocity, covering factor, gas density, and BLR radius we can also estimate the mass inflow rate. This is indeed similar to the accretion rate needed to power the AGN. We therefore assert that the BLR *is* the matter being accreted onto the black hole.

4.3. High accretion rate AGNs

Our *STOKES* modelling of scattering off infalling regions shows that the blueshifting increases with increasing column density (see Fig. 2). It also depends, of course, on the inflow velocity. The product of the column density and the inflow velocity gives the *mass accretion rate*. We therefore predict that high-accretion-rate AGNs (narrow-line Seyfert 1s; NLS1s) will show higher blueshiftings. Such large blueshifts, formerly interpreted as strong winds, have indeed been found in NLS1s (Sulentic et al. 2000; Xu et al. 2003; Leighly & Moore 2004).

4.4. The BLR is the accretion disc

The net inflow implies that

(a) there is a mechanism (a "viscosity") to transport angular momentum outwards and take away energy.

(b) energy is being generated as the BLR falls in.

The need for enough viscosity to get the observed inflow is the same as for classical accretion discs. It is now recognized that this viscosity comes from the magneto-rotational instability (MRI; Balbus & Hawley 1991). We propose that the MRI is also driving the inflow of the BLR.

Our deduced motions of the BLR shown in Fig. 3 and described in section 4.1 are qualitatively the same as the motions shown by MHD simulations of accretion discs (see, for example, the movies described by Hawley & Krolik 2001). Furthermore, Gaskell (2008) has pointed out that the size of the outer regions of a typical accretion disk is comparable to the size of the BLR. Given these similarities, we propose that the BLR *is* the outer accretion disc.

4.5. The narrow line region

As is discussed elsewhere in these proceedings, there is no doubt that *some* of the narrow-line region (NLR) is associated with the outflow in AGNs. However, the NLR also shows increasing blueshiftings with ionization just like the BLR, so Occam's razor suggests that much of the NLR is also inflowing.

5. Summary

Putting the results discussed above together we end up with the following picture of the AGN phenomenon:

- The BLR is the outer accretion disc.
- The BLR is the inner part of the torus.
- The BLR material flows in from the torus, through the BLR, and onto the black hole.
- The BLR motions are dominated by gravity, therefore $v^2 L^{1/2}$ can safely be used to estimate black hole masses.
- Magnetic fields also play a role in BLR kinematics, but radiation pressure is relatively unimportant.

Acknowledgements. Big thanks are due to Manolis Angelakis, Andrei Lobanov, and the other organizers for their efforts in putting the meeting together. It is a pleasure to acknowledge many useful discussion with Ski Antonucci. This research has been supported in part by the US National Science Foundation through grant AST 03-07912, and by the Space Telescope Science Institute through grant AR-09926.01. Development of the *STOKES* code was supported by the Hans-Böckler-Stiftung.

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