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What broad emission lines tell us about how active galactic nuclei work

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ABSTRACT

I review progress made in understanding the nature of the broad-line region (BLR) of active galactic nuclei (AGNs) and the role BLRs play in the AGN phenomenon. The high equivalent widths of the lines imply a high BLR covering factor, and the absence of clear evidence for absorption by the BLR means that the BLR has a flattened distribution and that we always view it near pole-on. The BLR gas is strongly self-shielding near the equatorial plane. Velocity-resolved reverberation mapping has long strongly excluded significant outflow of the BLR and shows instead that the predominant motions are Keplerian with large turbulence and a significant net inflow. The rotation and turbulence are consistent with the inferred geometry. The blueshifting of high-ionization lines is a consequence of scattering off inflowing material rather than the result of an outflowing wind. The rate of inflow of the BLR is sufficient to provide the accretion rate needed to power the AGN. Because the motions of the BLR are gravitationally dominated, and the BLR structure is very similar in most AGNs, consistent black hole masses can be determined. The good correlation between these estimates and masses predicted from the bulge luminosities of host galaxies provides strong support for the similarity of AGN continuum shapes and the correctness of the BLR picture presented. It is concluded that although many mysteries remain about the details of how AGNs work, a general overall picture of the torus and BLR is becoming clear.

1. Introduction

A broad-line region (BLR) is present in all AGNs accreting at moderate- to high-Eddington ratios. BLRs are important both because they are our best probe of how AGNs work and because of their potential for readily providing masses of supermassive black holes (SMBHs) back to the earliest times of galaxy formation. However, in order to be able to use BLRs to reliably estimate the masses of SMBHs it is essential to understand the structure and kinematics of BLRs. Over the last four decades there have been wide-ranging and, not infrequently, mutually contradictory views of the nature of the BLR (see reviews by Mathews and Capriotti (1985), Osterbrock and Mathews (1986), and Sulentic et al. (2000)). However, I believe that the situation is improving. I review here what I consider to be the clearest pointers to the underlying structure and kinematics of the BLR and I argue that, while there are certainly many interesting problems remaining, the basic picture is now becoming fairly secure. I furthermore believe that this picture applies to *all* BLRs because BLR equivalent widths and line ratios are remarkably similar, especially in the ultraviolet.

2. The structure of the broad-line region and torus

The two most basic questions about the BLR are "what does it look like?" and "how is it moving?" The traditional picture of the BLR of an AGN for over 40 years (and one which is widely depicted in cartoons of AGNs) has been that there is a central source emitting ionizing radiation roughly spherically, and that it is surrounded by a roughly spherical mist of cloudlets. This is depicted in the left-hand-panel of Fig. 1. Each individual cloud, if it is big enough, will have a structure as shown in the right-hand-panel of Fig. 1. It will be highly ionized on the front, and if it has a high-enough column density, it will be mostly neutral on the back. The front emits high-ionization lines such as He II, He I, O VI, N V, and C IV, while the back emits low-ionization lines such as Mg II, Ca II, O I, and Fe II. All these lines are well-known in AGNs.

The emissivity of each line as a function of distance from the front of the cloud can be calculated with the photoionization code CLOUDY (Ferland et al., 1998). Fig. 2 shows emissivities for some well-known lines.

Baldwin et al. (1995) showed that the sum of contributions from clouds with a distribution of cloud properties (densities and distances from the center) will automatically produce a total spectrum similar to what is observed from AGNs. This is the so-called LOC model.[1] This was important because it showed that no "fine-tuning" of cloud conditions was needed to explain AGN spectra.

Despite the success of the traditional picture in general, and the LOC model in particular, in explaining the overall spectrum of an AGN, the problem with this picture (see Gaskell et al., submitted for publication-b) is that to explain the strengths of the BLR lines

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[1] Ostensibly from "locally optimally emitting clouds."

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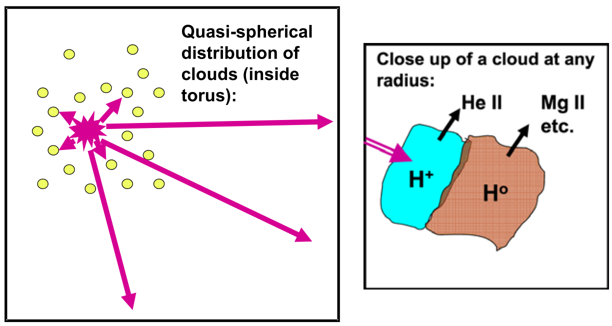

Fig. 1. The left frame shows a cartoon of a common traditional view of the BLR. The right frame shows a schematic close-up of an individual cloudlet.

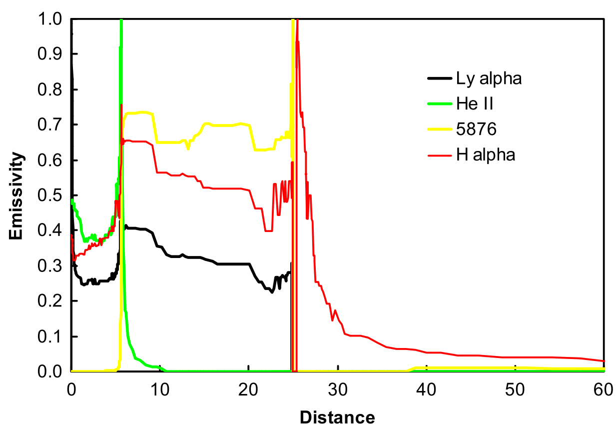

Fig. 2. Relative emissivity of four lines in a typical BLR cloudlet (normalized to a maximum emissivity of one for each line) versus distance (in arbitrary units) from the ionized face of the cloud.

the covering factor has to be large (50% or so), yet if this is so, and if the cloudlets are covering the central source uniformly, we ought to see Lyman continuum absorption by the BLR clouds. In fact Lyman continuum absorption due to the BLR is *never* convincingly seen (Antonucci et al., 1989 – see discussion in MacAlpine (2003) and Gaskell et al. (submitted for publication-b)). We believe, as proposed by S. Phinney (see Antonucci et al., 1989), that the need for a high covering factor plus the lack of Lyman continuum absorption *requires the BLR to have a flattened distribution and requires us to be viewing it through a hole.* This conclusion is supported by recovery of what is called the "transfer function" of some lines (the transfer function is the temporal response of a line to a delta-function event in continuum light curve). Transfer functions for low-ionization lines have always implied that there is little or no gas along the line of sight (Krolik et al., 1991; Horne et al., 1991; Mannucci et al., 1992; Pijpers and Wanders, 1994), and thus that at least the low-ionization gas in the BLR has a flattened distribution.

Having a high overall covering factor but a flattened distribution means that near the equatorial plane there will be a close to a 100% chance that any path will intersect a BLR cloud. The clouds will thus be self-shielding. Radiation from the central source can freely escape near the axis of symmetry, but is strongly diluted in the equatorial plane. This is schematically illustrated in Fig. 3.

It is easy to calculate the average radial dependence of the ionization and the emissivities of all the lines coming from cloudlets with a distribution such as in Fig. 3. The ionization structure of a single cloud in CLOUDY is now spread out in radius as illustrated schematically in Fig. 4. The horizontal axis in Fig. 2 can now be read as distance into the BLR rather than distance into an individual cloud. Our model is in fact very similar to the old "filling factor" model of MacAlpine (1972).

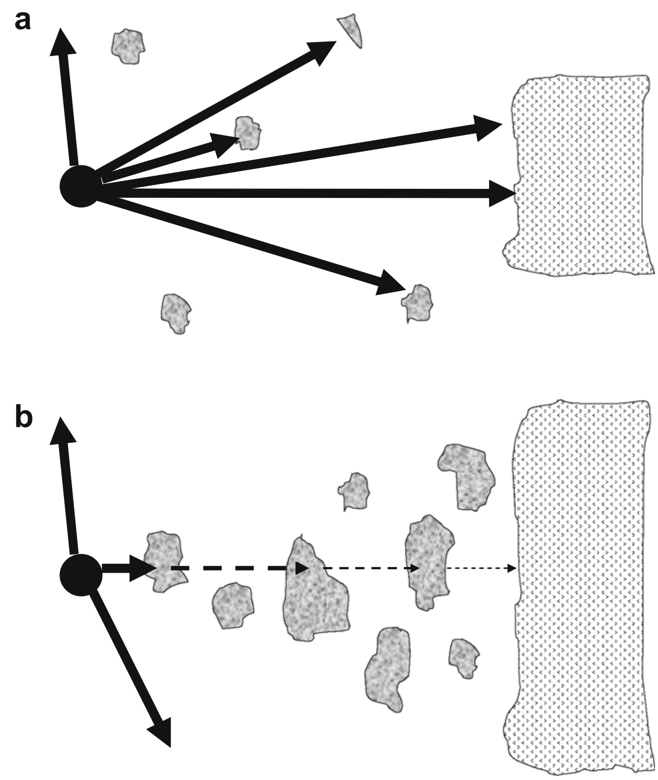

Fig. 3. Schematic cross section of the BLR and torus in a plane through the axis of symmetry. The torus is on the right. Ionizing radiation is attenuated in the equatorial plane, but can freely escape near the poles. Figure from Gaskell et al. (submitted for publication-b).

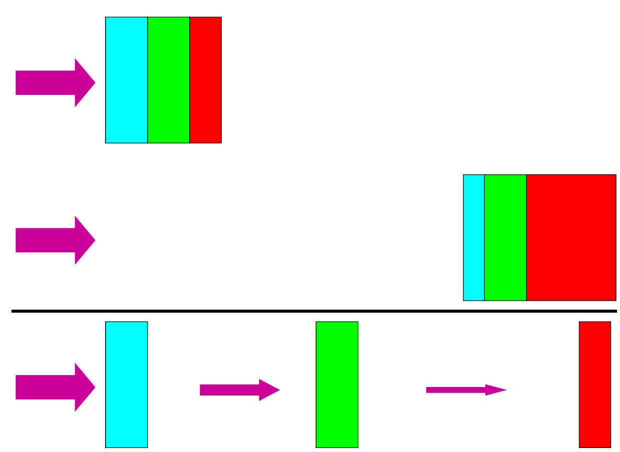

Fig. 4. Cartoon of the relationship between a traditional cloudlet model (top two thirds of the diagram) and the self-shielding model (bottom third). The different shadings symbolize three regions producing lines of differing degrees of ionization (cf. Fig. 3).

The earliest reverberation mapping of multiple lines (Gaskell and Sparke, 1986) showed that the high-ionization lines were coming from smaller radii than the low-ionization lines. High-ionization lines were also wider (e.g., Shuder, 1982; Mathews and Wampler, 1985). The radial ionization stratification of the BLR has been well confirmed by later reverberation mapping. The best reverberation-mapped AGN is NGC 5548. The horizontal axis of Fig. 5 (taken from Gaskell et al. (2008)) shows the reverberation-mapping time lags (i.e., the effective radii) for lines of a variety of ions from Clavel et al. (1991), Peterson et al. (1991), and Bottorff