What is the Broad Line Region?

Ari Laor

Physics Department, Technion, Haifa 32000, Israel

Abstract. What is the Broad Line Region (BLR) made of? What determines its location? Why is it sometimes missing? What controls its properties? Some recent results and new approaches which may shed light on these issues are briefly described.

1. Introduction

Imagine an Earth like civilization which developed on an isolated planet away from any star or galaxy. An astronomer there, faced with the spectrum of a spatially unresolved galaxy, will deduce it is made of dense gas “clumps” with \( n \sim 10^{17} \text{ cm}^{-3} \) and \( T \approx 3,000 – 30,000 \text{ K} \). Yet, he will have almost no idea of the true nature of galaxies. Here, on Earth, we may be facing a similar difficulty when trying to understand the BLR just based on its spectrum.

Photoionization calculations have reached a high level of sophistication, providing good constraints on the density, temperature, ionization level, chemical abundances and spatial distribution of the gas in the BLR (e.g. Ferland, these proceedings). However, these calculations do not reveal the origin of the gas. Is it made of individual “clouds” produced by e.g. bloated stars, tidally disrupted stars, a gravitationally unstable outer disk, or a wind interaction with SN remnants? Or, is it made of a continuous flow, e.g. a wind driven off an accretion disk by radiation pressure, magnetic pressure, or both? What determines the location of the BLR? Is it accretion disk physics? Furthermore, AGN show many emission lines with a large range in strengths and profiles, yet these emission properties are strongly correlated, suggesting there may be just a few free parameters which control these properties. What are these free parameters? In this short review I will briefly describe some of the progress made towards answering the above questions, and some potentially useful new approaches.

2. What is the BLR made of?

Photoionization calculations tell us the thickness of the line emitting layers, and their solid angle, but they do not tell us whether the gas is composed of many small units (e.g. bloated stellar atmospheres), a few larger units (e.g. tidally disrupted stars, wind interaction with supernovae remnants), or a single continuous flow (e.g. a disk outflow).

The number of “clouds” in the BLR, \( n_c \), and their size, \( r_c \), can be constrained based on the smoothness of the emission line profiles. The level of
fluctuations in the emission line profiles is proportional to $1/\sqrt{n_c}$ (see Capriotti et al. 1981 for a nice simulation), assuming the cloud velocities are randomly distributed within the line profile. The total solid area subtended by the BLR clouds is $\Omega_{\text{BLR}} = n_c \pi r_c^2 / 4 \pi R_{\text{BLR}}^2$, where $R_{\text{BLR}}$ is the BLR radius. Photoionization calculations indicate that $\Omega_{\text{BLR}} \approx 0.1 - 0.2$, and thus $r_c \approx R_{\text{BLR}}/\sqrt{n_c}$. Very high spectral resolution and S/N observations allow a large lower limits on $n_c$, and thus a tight upper limit on $r_c$, in particular in low luminosity objects where $R_{\text{BLR}}$ is expected to be small.

A recent study of the H$\alpha$ profile by Arav et al. (1998) using a very high S/N Keck spectrum placed a limit of $n_c > 3 \times 10^7$ in NGC 4151, where $\nu L_\nu (5100\ \text{Å}) = 7 \times 10^{42}$ erg s$^{-1}$. A similar study by Dietrich et al. (1999) in 3C 273, where $\nu L_\nu (5100\ \text{Å}) \approx 6 \times 10^{45}$ erg s$^{-1}$, yielded $n_c > 10^8$. In Figure 1 we show a high quality Keck spectrum of the H$\alpha$ profile in NGC 4395, the least luminous Seyfert 1 galaxy, where $\nu L_\nu (5100\ \text{Å}) = 6 \times 10^{39}$ erg s$^{-1}$. At this luminosity one expects $r_{\text{BLR}} \approx 10^{14}$ cm, if $R_{\text{BLR}} \propto L_\nu^{0.7}$ (Kaspi et al. 2000), or $R_{\text{BLR}} \approx 6 \times 10^{14}$ cm, if $R_{\text{BLR}} \propto L_\nu^{0.5}$. In the bloated stars scenario (Alexander & Netzer 1994) the size of the individual stars is $\sim 10^{14}$ cm, thus only a handful of such stars can be accommodated in the BLR of NGC 4395. This contrasts with the smoothness of H$\alpha$ in NGC 4395 which implies $n_c > 10^6$, and thus $r_c < 10^{11} - 10^{12}$ cm. The bloated stars scenario is therefore ruled out, together with other scenarios which involve individual units significantly larger than $10^{12}$ cm. The smoothness of the BLR profiles in the lowest luminosity AGN therefore suggests that the BLR most likely originates in a single continuous flow.
3. **What determines $R_{\text{BLR}}$?**

There are various models which attempt to explain the formation of the BLR based on accretion disk models. For example, it may arise in a gravitationally unstable outer disk, a disk outflow resulting from a combination of disk instability and a confining disk corona, or various other disk outflow mechanisms. However, some of the models do not make specific predictions for $R_{\text{BLR}}$, or otherwise predict that it should be a function of the black hole mass $M_{\text{BH}}$ in addition to $L$. These predictions may be inconsistent with the observations which indicate a rather tight relation of the form $R_{\text{BLR}} \approx 0.01(L_{\text{bol}}/10^{44})^{0.62-0.70}$ pc (Kaspi et al. 2000; Peterson et al. 2000).

Alternatively, $R_{\text{BLR}}$ may be set by dust sublimation. Dust embedded in the ionized gas strongly suppresses line emission when the ionization parameter $U > 0.01$. The column of the photoionized H II layer is $\Sigma_{\text{ion}} \approx 10^{23}U$ cm$^{-2}$, and the UV optical depth of dust is $\tau_{\text{dust}} \approx \Sigma/10^{21}$, which implies $\tau_{\text{dust}}(\text{H II}) \approx 100U$. Thus, when $U > 0.01$ the penetration of ionizing radiation to $\Sigma_{\text{ion}} > 10^{21}$ cm$^{-2}$ is suppressed by a “dust wall”, which converts the excess ionizing continuum to dust IR emission. The outgoing line emission is further suppressed due to absorption by the embedded dust. Since all dust sublimes below $R_{\text{sub}} \approx 0.02(L_{\text{bol}}/10^{44})^{0.5}$ pc, efficient line emission is restored at $R < R_{\text{sub}}$. Dust sublimation thus provides a *parameter free* mechanism for the outer boundary of the BLR (Laor & Draine 1993; Netzer & Laor 1993; Ferguson et al. 1997).

Just outside the BLR the gas cools mainly by dust IR emission, producing the ubiquitous 3 $\mu$m bump. Still further out low density gas with $U < 0.01$ produces the NLR emission. Further inward from the BLR the density of $U \lesssim 1$ gas increases, which leads to collisional destruction of the lines, and cooling mostly by atomic continuum radiation. Thus, the dust scenario implies that reprocessing gas is not necessarily located just at the BLR, but may be located at all radii, and the BLR is just where the gas cools efficiently by line emission.

The dust and disk BLR scenarios imply different responses of the BLR emission to ionizing continuum variations. If $R_{\text{BLR}}$ is set by the accretion disk structure then it is expected to respond to variations in the disk structure, which occur at most at the disk sound speed crossing time. Since the sound speed in a thin accretion disk is well below the local Keplerian speed, one expects changes in the BLR structure to occur on timescales much longer than the dynamical time $t_{\text{dyn}} = R_{\text{BLR}}/v_{\text{BLR}}$. Any other mechanism which produces physical changes in the gas distribution in the BLR cannot occur faster than $t_{\text{dyn}}$.

In the dust bounded BLR hypothesis, reprocessing gas is present at all radii, and changes in $R_{\text{BLR}}$ occur at the dust sublimation and reformation timescale. The sublimation timescale just outside the BLR is $t_{\text{subl}} \sim 10^{3-5}$ s, and one thus expects that an increase in $L$ should be accompanied by an increase in the broad line core flux from the outer BLR with a delay of only $\sim R_{\text{BLR}}/c$. Since $v_{\text{BLR}} \approx 0.01c$ the dust scenario allows profile variations which are 100 times faster(!) than the fastest variability timescale allowed by physical changes in the BLR (e.g. the disk BLR scenario).

When $L$ decreases dust can reform at smaller radii, again maintaining the $R_{\text{BLR}} \propto L^{0.5}$ relation. However, dust condensation is a much slower process ($t_{\text{cond}} \sim 10^{7}$ s), and since nucleation cannot start in a $\sim 10^{4}$ K photoionized gas, it will take $\geq t_{\text{dyn}}$ to get a fresh supply of dusty gas into the outer BLR.
Thus, if $R_{BLR}$ is set by dust sublimation then $R_{BLR}(L, t)$ will show a hysteresis effect, i.e. it will follow the $R_{BLR} \propto L^{0.5}$ relation when $L$ increases, but when $L$ decreases $R_{BLR}$ will respond with a delay of at least $t_{dyn}$. In the disk scenario there should not be any clear asymmetry in the response of $R_{BLR}$ to luminosity increases vs. decreases. Finally, a corresponding hysteresis effect should be observed in the response of the 3 $\mu$m dust emission to variations in $L$.

4. What controls the existence of a BLR?

Some AGN do not show any broad emission lines. While there is strong evidence that the BLR is obscured in many AGN, there are other cases where the BLR appears to be truly missing (termed true type 2 AGN). Why do some AGN do not have a BLR?

The distribution of observed broad line widths appears to have a cutoff at a FWHM of about 25,000 km s$^{-1}$ (Strateva et al. 2003), though it is not entirely clear if this cutoff is due to a physical mechanism, or if it is due to some observational limitation. This cutoff implies that the BLR will not be observable in AGN with $L < L_{crit}$, as explained below. If dust sublimation sets $R_{BLR} \propto L^{0.5}$, and if gravity sets the BLR line widths $\Delta v \propto \sqrt{M_{BH}/R_{BLR}}$, then these relations imply that $\Delta v > 25,000$ km s$^{-1}$ once $L < L_{crit} = 10^{25.8}(M_{BH}/M_{\odot})^2$ erg s$^{-1}$ (Laor 2003). Thus, if the BLR is bounded from the outside by the dust sublimation radius, and from the inside by the radius where $\Delta v > 25,000$ km s$^{-1}$, then at $L = L_{crit}$ the inner and outer boundaries merge, and no region where the BLR can survive exists once $L < L_{crit}$. Thus all AGN at $L < L_{crit}$ should not have a BLR.

If the BLR is produced by an outflow from a dense, thin, accretion disk, then the flow may not exist below some critical value of $L/L_{Edd}$, either because of the outflow driving mechanism properties (Nicastro 2000), or because the disk disappears altogether and becomes a hot and dilute thick inflow, which may occur at $L/L_{Edd} \lesssim 10^{-3} - 10^{-4}$.

Thus, it will be worthwhile to obtain high quality observations of low luminosity AGN (where the host galaxy light has been carefully subtracted) in order to 1. determine if the cutoff at $\Delta v > 25,000$ km s$^{-1}$ is real, rather than a selection effect. 2. Determine the critical luminosity which separates true type 2 AGN from true type 1 AGN. These observations will provide important clues for the physical mechanisms which control the existence of the BLR (see Laor 2003 for further discussion, including the narrow line profiles).

5. What controls the line strengths/ratios?

The seminal study of Boroson & Green (1992, hereafter BG92) established the presence of a set of correlations among the H$\beta$, optical Fe II, He II, and [O III]$\lambda\lambda$4959,5007 emission line properties. In particular they found that a narrow H$\beta$ line is associated with a weak [O III], strong optical Fe II, and a blue excess asymmetric H$\beta$ profile. BG92 speculated that the physical parameter underlying these correlations (part of their eigenvector 1, or EV1) is $L/L_{Edd}$, in the sense that objects with a narrow H$\beta$ have a high $L/L_{Edd}$.
The main components of EV1 were later found to be strongly correlated with the X-ray emission properties, such that objects with a narrow Hβ tend to have a steep soft X-ray slope. A steep soft X-ray slope was independently suggested to be associated with a high \( L/L_{\text{Edd}} \), which agreed with the BG92 speculation. Further significant support for \( L/L_{\text{Edd}} \) as the driving parameter came with the recent findings that the Hβ FWHM allows a good quantitative estimate of \( M_{\text{BH}} \), and thus that a narrow Hβ is generally associated with a high \( L/L_{\text{Edd}} \) (see Laor 2000 for a recent review).

Wills et al. (1999) extended the BG92 correlation analysis to the UV, and found strong correlations of UV emission line ratios with the the EV1 optical emission line parameters. In particular, a narrow Hβ is associated with weak C IV, weak C III], and relatively strong Si IV+O IV] and N V emission. These trends may reflect an increase in the mean BLR density (increasing Si III]/C III]; Gaskell 1985; Laor et al. 1997), and metallicity (increasing N V/C IV; Hamann & Ferland 1999) with increasing \( L/L_{\text{Edd}} \). Another very interesting feature is the apparent anti-correlation between the UV Fe II and optical Fe II emission, indicated by the spectral principal component analysis of Shang et al. (2003). This effect is expected with increasing optical depth in the Fe II emitting gas, as an increased number of resonance scattering of UV Fe II photons leads to down conversion to optical Fe II photons. The increase in optical depth may be due to an increase in the gas Fe abundance and overall metalicity.

A possible scenario for the above trends in the BLR properties with \( L/L_{\text{Edd}} \) could be through some large scale process (interaction?) which leads to a high rate of gas infall to the center, resulting in a nuclear starburst, and thus metal enrichment of the gas which continues its infall to the center, producing a high density high metallicity BLR surrounding a high accretion rate AGN. Alternatively, Warner et al. (2003) suggest that the BLR metalicity is driven by \( M_{\text{BH}} \), rather than \( L/L_{\text{Edd}} \). This is supported by the known relations between metalicity, bulge mass, and \( M_{\text{BH}} \), in nearby inactive galaxies.

Further progress on the nature of the primary driver of the above relations can be made by making direct correlations of the various line emission properties with our best estimates of \( M_{\text{BH}} \) and \( L/L_{\text{Edd}} \) using well defined and complete samples with high quality optical and UV data\(^1\). Finally, the starburst induced high \( L/L_{\text{Edd}} \) scenario can be tested through high resolution multicolor imaging with the HST of well defined samples of nearby AGN with high and low \( L/L_{\text{Edd}} \).

---

6. **What controls the line shapes?**

The peaks of the high ionization broad emission lines are generally blueshifted with respect to the low ionization lines, and their profiles tend to show blue excess asymmetry, while the low ionization lines show less asymmetry (Gaskell 1982; Wilkes 1984, Richards et al. 2002)\(^2\). In a given object the line velocity

---

\(^1\)Note that the high ionization lines, in particular C IV, may not provide \( M_{\text{BH}} \) estimates as good as those obtained by the Balmer lines (Baskin & Laor, these proceedings).

\(^2\)Qualitatively similar effects are seen in the narrow emission line profiles (Heckman et al. 1981, ApJ, 247, 403; Vanden Berk et al. 2001, AJ, 122, 549).
shift and asymmetry increase with the ionization level (Laor et al. 1997), and both effects appear to be strongest in narrow Hβ AGN (Baldwin et al. 1996). Given the EV1 correlations mentioned above, it appears that the two effects are largest in objects with a high $L/L_{Edd}$. Such a relation may be formed by the following scenario. Radiation pressure ablates the face of the BLR “clouds”, creating a radial outflow. As the outflow accelerates, the density drops and the ionization level increases, creating the increased line shift and asymmetry (the redshifted outflow is presumably obscured). Furthermore, as $L/L_{Edd}$ increases the column density of the radiatively accelerated layer increases, creating the apparent trends with $L/L_{Edd}$. Alternatively, Richards et al. suggest the observed trends may be driven by an inclination effect.

The origin of the line asymmetry can be verified by reverberation mapping of objects with highly asymmetric lines. If it is due to an outflow then the blue wing should respond faster than the rest of the line. The nature of the primary physical driver can be explored by correlating the observed properties against $L/L_{Edd}$, and by comparing the observed trends with physical outflow models.

References

Alexander, T. & Netzer, H. 1994, MNRAS, 270, 781
Arav, N. et al. 1998, MNRAS, 297, 990
Baldwin, J. A. et al. 1996, ApJ, 461, 664
Boroson, T. A., & Green, R. F. 1992, ApJS, 90, 109 (BG92)
Capriotti, E., Foltz, C., & Byard, P. 1981, ApJ, 245, 396
Dietrich, M., et al. 1999, A&A, 351, 31
Ferguson, J. W., et al. 1997, ApJ, 487, 122
Gaskell, C. M. 1982, ApJ, 263, 79
Gaskell, C. M. 1985, ApJ, 291, 112
Hamann, F. & Ferland, G. 1999, ARA&A, 37, 487
Kaspi, S., et al. 2000, ApJ, 533, 631
Laor, A. & Draine, B. T. 1993, ApJ, 402, 441
Laor, A., Jannuzi, B. T., Green, R. F., & Boroson, T. A. 1997, ApJ, 489, 656
Laor, A. 2000, New Astronomy Review, 44, 503
Laor, A. 2003, ApJ, 590, 86
Netzer, H. & Laor, A. 1993, ApJ, 404, L51
Nicastro, F. 2000, ApJ, 530, L65
Peterson, B. M. et al. 2000, ApJ, 542, 161
Richards, G. T., et al. 2002, AJ, 124, 1
Shang, Z. et al. 2003, ApJ, 586, 52
Strateva, I. V. et al. 2003, AJ, 126, 1720
Warner, C., Hamann, F., & Dietrich, M. 2003, ApJ, 596, 72
Wilkes, B. J. 1984, MNRAS, 207, 73
Wills, B. J. et al. 1999, ApJ, 515, L53