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The origin of the broad line region in active galactic nuclei

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Abstract. Reverberation mapping measurements allowed to probe the distance between the broad line region and the continuum source in the AGNs. This important result does not give direct answer about geometry and dynamics of the broad lines region. We used reverberation mapping measurements to estimate effective temperature of the accretion disc underlying the broad line region in the Seyfert galaxies. Derived temperature value is universal and for every object is close to 1000 K — below dust sublimation temperature. Presence of the dust allows developing the broad line region by the dust driven wind. On the higher altitudes dust evapourates when striked by the side UV radiation, so the final picture is failed wind geometry.

Key words. galaxies: active – galaxies: Seyfert – quasars: emission lines

1. Introduction

Lines with width of few thousands km/s are signature of active galactic nuclei. Broad line region (BLR) is the region where broad lines are produced. Emitting medium is at least ten times more distant from the central black hole than the continuum emitting region. Position of the BLR was concluded from reverberation measurements. In the reverberation mapping technique we measure time time lag between continuum brightening and emission line brightening.

Important properties of the BLR medium is that it is in the Keplerian motion but additional velocity components should be present (e.g. Done & Krolik 1996; Kollatschny 2003; Collin et al. 2006) and the emitting medium is concentrated close to the accretion disc. Netzer & Laor (1993) and Suganuma et al. (2006) pointed out that the outer part of the BLR meets dusty/molecular torus. As indicated by works of Nicastro et al. (2003), Czerny et al. (2004) and Cao (2010), cold disc is required by existence of the BLR. In our work we adress outlined issues.

1.1. Reverberation formula

Reverberation mapping measurements for nearby Seyfert galaxies and low luminous quasars was made by following authors Wanders et al. (1993), Salamanca et al. (1994), Stirpe et al. (1994), Winge et al. (1995), Winge et al. (1996), Santos-Lleó et al. (1997), Peterson et al. (1998), Dietrich et al. (1998), Collier et al. (1998), Kaspi et al. (2000), Peterson et al. (2000), Santos-Lleó et al. (2001), Peterson et al. (2002), and references

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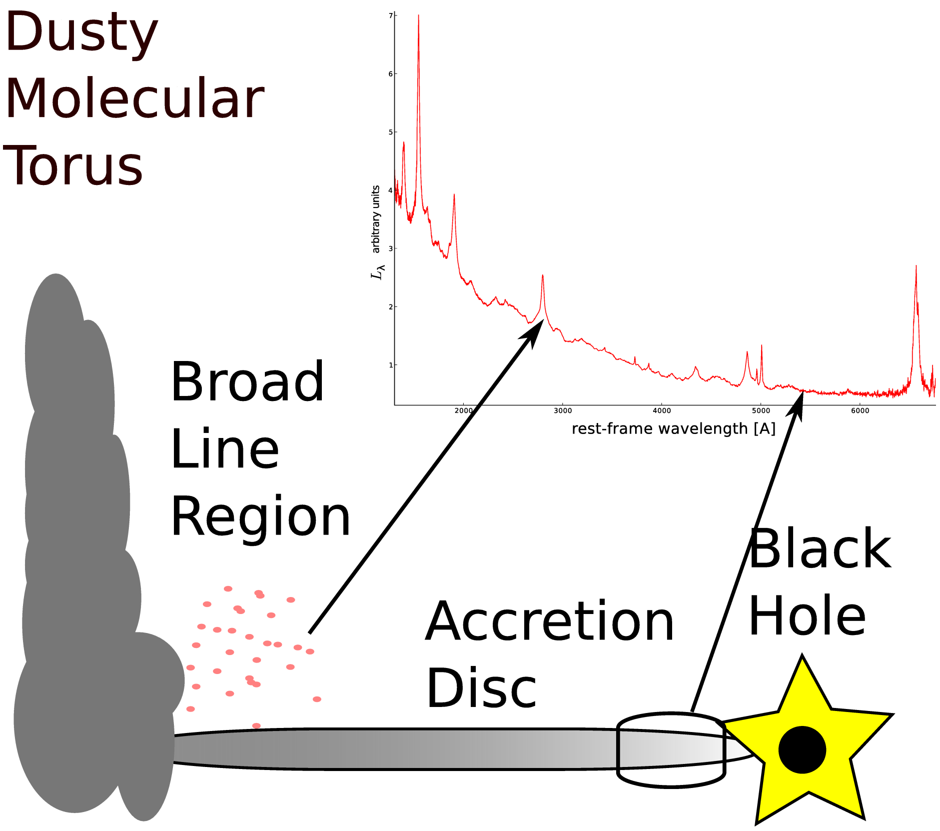

Fig. 1. Schematic view of an AGN together with mean quasar spectrum (Richards et al. (2003) composite). Optical/UV continuum is produced close to the black hole, in the accretion disc region extending from tens to hundred Schwarzschild radii. Broad emission lines are produced further away from the center — more than thousands Schwarzschild radii away from the black hole. The region smaller than dusty torus (parsec scale) is not spatially resolved.

Table 1. Effective temperature of the disk underlying BLR for sources from the reverberation sample. Bolded values were computed from Bentz et al. mean time delays.

Name	T_{eff} [K]
Mrk 335	1302
	1731
	1427
PG 0026+129	903
PG 0052+251	913
Fairall 9	1516
Mrk 590	951
	835
	605
	783
	749
3C 120	962
Ark 120	724
	648
	808
Mrk 79	1859
	1318
	1245
	1307
PG 0804+761	690
PG 0844+349a	1181
Mrk 110	913
	1109
	633
	897
PG 0953+414	858
NGC 3227	1058
	901
	787
NGC 3516	995
NGC 3783	1020
NGC 4051	584
NGC 4151	550
PG 1211+143	826
PG 1226+032	986
PG 1229+204	662
NGC 4593	1890
PG 1307+085	838
IC 4329Ab	683*
Mrk 279	1227
PG 1411+442	575
PG 1426+015	748
Mrk 817	1203
	1274
	707
	990
PG 1613+658	1607
PG 1617+175	756
PG 1700+518	828
3C 390.3	934
Mrk 509	587
PG 2130+099	1836
NGC 7469	2408
NGC 5548	828
	694
	940
	968
	1068
	1094
	864
	987
	792
	788
	772
	1481
	825
	1289
	859

* time delay taken from Winge et al. (1996).

therein; Bentz et al. (2006), Denney et al. (2006), Bentz et al. (2007), Grier et al. (2008). Bentz et al. (2009) collected data from the literature and corrected luminosities for the host galaxy contamination.

We took the sample of host galaxy corrected measurements and refitted time delay — continuum luminosity relation.

The Bentz et al. relation was:

$$\log R_{BLR}(H\beta)[lt.days] \sim 0.519^{+0.063}_{-0.066} \log L_{5100} \quad (1)$$

We refitted relation with fixed coefficient:

$$\log R_{BLR}(H\beta)[lt.days] = \mathbf{0.5} \log L_{44,5100} + 1.516 \pm 0.043 \quad (2)$$

1.2. Geometrical consideration

We assumed that in most cases we see mainly BLR part from the opposite site of the disc as presented in Figure 2.

Thus geometrical correction to the radius:

$$r = \frac{R_{BLR}}{1 + \sin i} \quad (3)$$

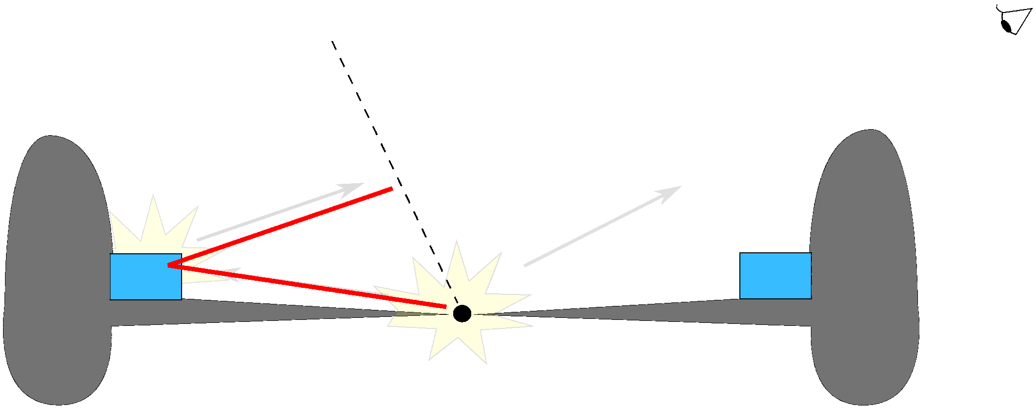

Fig. 2. In the reverberation mapping technique an observer measures variability on different wavelengths. When the central continuum source shows brightening then after some time brightening of emission lines is detected. We assumed that on average we mainly see irradiation of the BLR from behind the black hole. Thus the observed time lag is the interval light needs to pass distance marked as red solid line.

where R_{BLR}, as above, means measured time delay and i is the inclination angle.

1.3. Monochromatic luminosity

The monochromatic luminosity at 5100 Å can be calculated from Tripp et al. (1994) formula (corrected by Nikołajuk):

$$\log L_{44,5100} = \frac{2}{3}\log(M\dot{M}) + \log\cos i - 43.8820 \quad (4)$$

This formula is very usefull since it connects important global parameters in simple relation. It will be used to derive $M\dot{M}$.

1.4. Effective temperature

The effective temperature at the radius, r, based on the Shakura-Sunyaev accretion disk theory can be estimated from equation

$$\sigma_B T_{\rm eff}^4 = \frac{3GM\dot{M}}{8\pi r^3} \quad (5)$$

When we combine previous Equations 2, 3, 4 and 5, the dependence on the unknown mass and the accretion rate vanishes:

$$T_{\rm eff} \sim \left[\frac{3G(1+\sin i)^3}{8\pi\sigma_B(\cos i)^{3/2}}\right]^{1/4} \quad (6)$$

When we use the mean inclination (39.2°) we get:

$$T_{\rm eff} = 995 \pm 74\,{\rm K} \quad (7)$$

This value is interesting since it is close to the critical temperature at which the dust can form. The distance to the BLR is smaller than the distance to the dusty torus $R_{dust} \sim 0.4 L_{45}^{1/2}$ pc (Nenkova et al. 2008).

We also computed the temperatures for individual objects. If we derive relation on $M\dot{M}$ from equation 4: $\log(M\dot{M}) = \frac{3}{2}(\log L_{44,5100} - \log\cos i + 43.8820)$
and use geometrical correction 3 together with effective temperature formula 5 we have another estimation of the temperature under the BLR.

For all sources apart from NGC 5548:

$$T_{\rm eff} = 1030 \pm 61\,{\rm K} \quad (8)$$

For NGC 5548:

$$T_{\rm eff} = 956 \pm 56\,{\rm K} \quad (9)$$

1.5. SED influence

In work of Vasudevan & Fabian (2008) spectral energy distributions of Seyfert galaxies were presented. We present computed ionizing radiation luminosity by integrating SEDs

Table 2. The dimensionless ratio of the luminosity above 1 Ry to the monochromatic luminosity at 5100 Å, $LR = L_{1\mathrm{Ry}-100\mathrm{keV}}/\lambda L_\lambda(5100\text{Å})$

Name	*LR*
3C 120	7.89
3C 390.3	8.28
Akn 120	2.92
Fairall 9	2.34
Mrk 110	13.33
Mrk 279 (1)	8.71
Mrk 279 (2)	9.10
Mrk 279 (3)	8.73
Mrk 335 (1)	13.89
Mrk 335 (2)	23.14
Mrk 509	3.17
Mrk 590	6.75
Mrk 79	5.12
NGC 3227 (1)	6.28
NGC 3227 (2)	4.13
NGC 3516	2.10
NGC 3783 (1)	4.97
NGC 3783 (2)	4.05
NGC 4051 (1)	6.49

Name	*LR*
NGC 4051 (2)	11.29
NGC 4151 (1)	7.92
NGC 4151 (2)	7.97
NGC 4151 (3)	9.04
NGC 4593	15.59
NGC 5548	4.09
NGC 7469	14.35
PG 0052+251	2.91
PG 0844+349	6.48
PG 0953+414	4.07
PG 1211+143 (1)	3.16
PG 1211+143 (2)	2.56
PG 1226+023	4.76
PG 1229+204	4.34
PG 1307+085	1.27
PG 1411+442	0.37
PG 1426+015	0.54
PG 1613+658	1.92
PG 2130+099	0.60

in the spectral range 1Ry – 100keV. In Table 2 we computed luminosity ratios defined as $LR = L_{1\mathrm{Ry}-100\mathrm{keV}}/\lambda L_\lambda(5100\text{Å})$. There is difference between Seyfert 1 (S1) and narrow line Seyfert 1 (NLS1) galaxies. NLS1s have systematicaly higher $LR = 10.6 \pm 2.6$ while S1s have mean $LR = 5.5 \pm 0.7$. We checked also correlation between $T_{\mathrm{eff}}$and *LR*. It seems that weak positive correlation exist between the effective temperature for each object and its *LR*.

2. Interpretation

Derived temperature, 1000 K, allows dust sublimation in the accretion disc atmosphere on the BLR characteristic radius. Dusty wind arises driven by the thermal radiation from the underlaying disc. Gas dragged by dust grains follows up and leaves the disc atmosphere. On certain altitudes wind matter is exposed on the UV radiation from the close vicinity of the black hole. UV photons ionise gas and cause dust grains evapouration. As dust is missing some fraction of the matter can fall down towards the accretion disc.

2.1. Another results supporting this picture

Few authors have suggested necessity of two components: inflow and outflow (Done & Krolik (1996), Elvis (2000), Ferland et al. (2009), Gaskell (2009), Shapovalova et al. (2010)). Some of the evidences supporting this are relative shifts between emission lines — e.g. shifted iron emission. Also need of additional mechanical heating in the process of Low Ionization Lines production have been emphasised in the theoretical works of Collin-Soufrin et al. (1988), Bottorf & Ferland (2002), Shapovalova et al. (2004), Shapovalova et al. (2010).

2.2. Alternative hypotheses explaining existence of the BLR

Nicastro (2000) has suggested that BLR originate in the transition from the radiation pressure to gas pressure within the disc. Position of that region depend on parameters like $R_{ab} \propto$

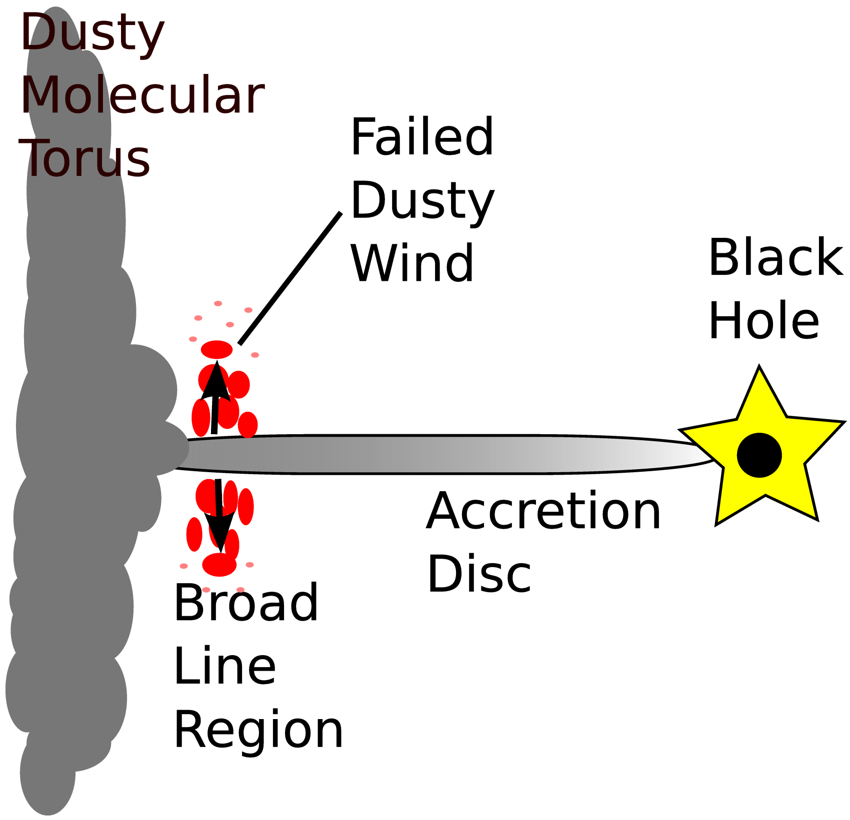

Fig. 3. The BLR region cover the range of the disk with the effective temperature lower than 1000 K: the dusty wind rises and then fails when exposed to the radiation from the central source (Czerny & Hryniewicz 2011). The dusty torus is the disk range where the irradiation does not destroy the dust and the wind flows out. Concept of the figure comes from work of Czerny & Hryniewicz (2011).

$M^{23/21}\dot{m}^{16/21}$ thus relation betwee BLR position and continuum luminosity as follows:

$$R_{BLR}^{radpres} \propto L_{5100}^{23/28}\dot{m}^{3/14}, \quad (10)$$

In contrary Collin & Hure (2001) have suggested that BLR may be supported by transition from non-selfgravitating to self-gravitating disc structure. This transition can occur in region b or c in Shakura & Sunyaev disc model thus there are two possible relations:

$$R_{BLR}^{sg} \propto L_{5100}^{1/36}\dot{m}^{-83/54} \quad \text{(region b)}$$

$$R_{BLR}^{sg} \propto L_{5100}^{-7/60}\dot{m}^{-37/90} \quad \text{(region c)} \quad (11)$$

Above alternatives are different from the reverberation result $R_{BLR} \propto L_{5100}^{1/2}$.

3. Probing BLR evolution

One of the possible test of dusty BLR wind hypothesis could be investigation of the weak line quasars (WLQ). In SDSS 094533.99+100950.1 only low ionization lines were detected with higher significance level. Although MgII emission line is rather broad (FWHM ≈ 6000 km s^{-2}) which allows black hole mass estimation. Explanation proposed by Hryniewicz et al. (2010) suggests that this WLQ is catched in the BLR developing phase. Later works presented by Czerny & Hryniewicz (2011) and Laor & Davis (2011) have put constraints on the accretion disc parameters — spin and inclination angle. In addition preliminary photoionization simulations presented by Hryniewicz (2011) has showed that the BLR in SDSS 0945+1009 is well explained by rather compact region occupied by a matter with similar density as the accretion disc atmosphere, which in principle is consistent with the developing BLR statement. Prefered inclination angle values in SDSS 0945+1009 are low, so the disc could be seen top-view. This fact together with the MgII line broadness supports our BLR "boiling" geometry scenario of the BLR LIL part.

4. Conclusions

We found that accretion disc effective temperature underlying the broad line region is universal value 1000 K. Effective temperature computed for each object is consistent with theoreticaly expected value. Temperature is low enough to allow dust grains sublimation. Thus we concluded that BLR is developed by dusty wind arised from the accretion disc. Dust on higher altitudes above disc atmosphere is exposed on side UV radiation from the center and in consequence evaporates. This behavior leads to failed wind or "boiling motion". Our hypothesis of dust driven wind applies at least to low ionization part of the BLR, where Hβ and MgII lines are produced.

5. Discussion

JAMES BEALL: Will the BLR clouds generated on the accretion disk near the torus orbit the black hole or remain near the disk?

KRZYSZTOF HRYNIEWICZ: I would expect that most of the matter will remain concentrated close to the disc. Although I do not know exact answer. We will try to address this question in further simulations of the BLR kinematics.

MANUEL PERUCHO: You have said that the BLR clouds are close to the accretion disk. There is a lot of work done about the interaction of jets with clumpy regions. Do you have any conclusions from your work regarding those regions in the path of the jet?

KRZYSZTOF HRYNIEWICZ: I speculate that in case of matter from failed wind it should not travel to direct vicinity of the jet. Although if we consider clouds behind border of the torus, where dust effectivly preveil, strong wind can drive material far away. My guess is that we would rather find some molecular matter or narow line region medium (0.1 and more kpc away from the black hole) closer to the jet axis than BLR clouds (0.1 pc scale radius).

KEN EBISAWA's Comment: Recent X-ray observations of AGN suggest most spectral variations are explained by partial absorption by BLR clouds which have internal ionization structure. I would suggest to continue theoretical study of BLR clouds to estimate parameters such as column density and internal ionization structure. Then we can directly compare observation and theory.

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