Feeding Compact Objects: Accretion on All Scales
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Dusty origin of the Broad Line Region in active galaxies

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Abstract. The most characteristic property of active galaxies, including quasars, are prominent broad emission lines. I will discuss an interesting possibility that dust is responsible for this phenomenon. The dust is known to be present in quasars in the form of a dusty/molecular torus which results in complexity of the appearance of active galaxies. However, this dust is located further from the black hole than the Broad Line Region. We propose that the dust is present also closer in and it is actually responsible for formation of the broad emission lines. The argument is based on determination of the temperature of the disk atmosphere underlying the Broad Line Region: it is close to 1000 K, independently from the black hole mass and accretion rate of the object. The mechanism is simple and universal but leads to a considerable complexity of the active nucleus surrounding. The understanding the formation of BLR opens a way to use it reliably - in combination with reverberation measurement of its size - as standard candles in cosmology.

Keywords. Accretion, accretion disks; Black hole physics; Cosmology

1. Introduction

Increasing spatial resolution allows to observe directly parts of active galactic nuclei. However, the innermost part is still unresolved and the information about its geometrical structure comes from spectroscopy. This structure is very complex, so vigorous discussions of inflow/outflow are still going on. Among this unsolved problems is the origin of Broad Emission Lines.

Broad Emission Lines come from a specific Broad Emission Line Region (BLR), as seen in well separation of the Broad and narrow components in the emission lines of active galaxies. They cover significant fraction of the AGN sky, between 10 and 30 %, as implied by their luminosity, but they are rarely seen in absorption (for rare exceptions, see e.g. Risaliti *et al.* 2011) which argues for the flat configuration (e.g. Nikolajuk *et al.* 2005, Collin *et al.* 2006), mostly hidden inside the outer dusty-molecular torus. The motion of the material is roughly consistent with circular Keplerian orbits (Wandel *et al.* 1999), but with significant additional velocity dispersion. Careful studies indicate two components of the BLR (Collin-Souffrin *et al.* 1988): High Ionization Lines (HIL; e.g. CIV) and Low Ionization Lines (LIL; e.g. Hβ, Mg II). HIL show blueshift with respect to narrow lines and they are considered to be comming from outflowing wind. LIL do not show significant shift so cannot come from outflow, but the region cannot be supported by the hydrostatic equilibrium. Therefore, the dynamics of LIL is difficult to understand from theoretical point of view, and it is also not resolved by direct monitoring (e.g. Peterson *et al.* 2004).

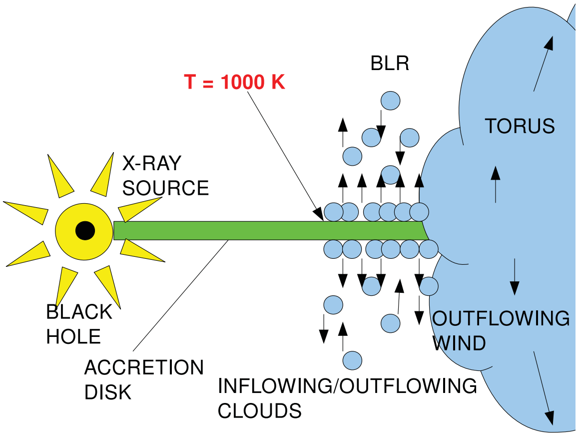

Figure 1. Schematic picture of the formation of the BLR. The outflow starts where the disk effective temperature drops below 1000 K and dust formation can proceed. Dusty outflow changes into a failed wind above the disk, where the irradiation leads to dust evaporation, the radiation pressure suport rapidly decreases and the material falls back onto the disk.

2. Accretion Disk Temperature at the Onset of BLR

Here we show that the combination of the simplest accretion disk theory and the reverberation measurement of the BLR distance leads to surprising conclusion: the effective temperature of the accretion disk at the radius measured from reverberation is universal and equal to 1000 K. The argument goes in the following way (for more details, see Czerny & Hryniewicz 2011).

The measurements of the delay of the Hβ line with respect to the continuum at 5100 A for close to 40 objects allowed to determine the relation between the BLR size, as measured from such delay, and the monochromatic flux (Kaspi *et al.* 2000, Peterson *et al.* 2004). The most recent form of this relation, corrected for the starlight contamination, was derived by Bentz *et al.* (2009). This relation can be written in the following way

$$\log R_{BLR}[\mathrm{H}\beta] = 1.538 \pm 0.027 + 0.5 \log L_{44,5100}, \tag{2.1}$$

where $R_{BLR}[\mathrm{H}\beta]$ is in light days and $L_{44,5100}$ is the monochromatic luminosity at 5100 Åmeasured in units of 10^{44} erg s^{-1}. The value 0.027 is the error in the best-fit vertical normalization.

Now, from the simplest theory of the alpha disk (Shakura & Sunyaev 1973) we can find the monochromatic flux. The asymptotic formula is usually known in the form

$$L_\nu \propto \nu^{1/3}, \tag{2.2}$$

but the proportionality coefficient is also known, and depends on the black hole mass, M, and accretion rate, $\dot{M}$ as $(M\dot{M})^{2/3}$. Taking into account this dependence, physical constants and fixing the frequency at the value corresponding to the wavelength 5100 A, we have

$$\log L_{44,5100} = \frac{2}{3}\log(M\dot{M}) - 43.8820 + \log\cos i. \tag{2.3}$$

This formula allows us to calculate the BLR radius from the Eq. 2.1, if the product of $(M\dot{M})$ is known.

The Shakura-Sunyaev accretion disk theory allows us to calculate the effective temperature of the disk at that radius as a function of the black hole mass and accretion

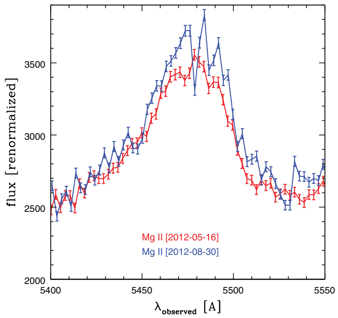

Figure 2. Two observations of the Mg II line of the quasar LBQS 2113-4538, separated by ∼ 100 days. The shape of the line has clearly changed, and the line intensity has changed by 9 %, which allows for a systematic monitoring of this source.

rate

$$T_{eff} = \left(\frac{3GM\dot{M}}{8\pi r^3 \sigma_B} \right)^{0.25}, \tag{2.4}$$

where σ_B is the Stefan-Boltzmann constant. Since BLR is far from the central black hole, the inner boundary effect can be neglected.

When we combine Eqs. 2.1, 2.3, and 2.4, the dependence on the unknown mass and accretion rate vanishes, and we obtain a single value for all the sources in the sample

$$T_{eff} = 995 \pm 74\mathrm{K}, \tag{2.5}$$

where the error reflects the error in the constant in Eq. 2.1. We stress that the resulting value does not depend either on the black hole mass or accretion rate. The value is universal, for all sources.

3. BLR Formation Mechanism

The value of the universal temperature of ∼ 1000 K immediately hints that the physical mechanism of the BLR formation is related to the dust formation in the accretion disk atmosphere. The dust opacity is large, and even moderate radiation flux from the underlying disk can push the dusty material off the disk surface. This dusty outflow, however, cannot proceed too far from the disk plane. Lifted material is irradiated by the strong UV and X-ray flux from the central region, the material heats up, the dust evaporates, the opacity rapidly decreases, and in the absence of the strong radiation pressure the material fall back again onto the disk surface. Therefore, such a failed wind can account for lifting the material relatively high above the disk plane and at the same time does not give a strong systematic signatures of outflow since both outflow and inflow are present.

The overall geometry is shown in Fig. 1. The BLR region starts were the disk effective temperature, without irradiation from the central region, falls below 1000 K, and it ends up at larger distance when the material has the temperature below 1000 K even if the irradiation is included. This outer radius marks the transition to the outer dusty/molecular torus, where the irradiation is too weak to lead to dust evaporation and the outflow proceeds.

4. Application to the Dark Energy Study

It was already proposed by Watson *et al.* (2011) that Eq. 2.1 can be used to determine the distance to a quasar in a way independent from the redshift. Reverberation measures the BLR size directly from the time delay, and Eq. 2.1 gives us the intrinsic monochromatic luminosity. This, combined with the observed monochromatic luminosity, gives the luminosity distance to the source. If a number of distant quasars are measured, a luminosity distance vs. redshift diagram can be constructed. Our interpretation of the BLR formation supports the view that Eq. 2.1 can apply to high redshift objects as well, since the mechanism is based on dust formation, this in turn is connected with medium metalicity, and the metalicity of distant quasars is known to be roughly solar.

With this in mind, we started a monitoring program with the Southern Africal Large Telescope. We choose intermediate quasars and Mg II line which belongs to LIL class, as Hβ, and should not show rapid intrinsic variations characteristic fo CIV line. Two test observations already performed show clear variation of the line intensity and shape in observations separated by ~ 100 days. We now perform Monte Carlo simulations in order to optimize the project.

5. Conclusions

We propose that dust forms not only in the outer dusty/molecular torus, but also closer in, in the non-irradiated thin disk atmosphere. This dust is responsible for the formation of the failed wind which accounts for the formation of the Low Ionization Line part of the Broad Line Region.

This interpretation automatically explains why the size of the BLR scales with the square root of the monochromatic, instead of bolometric, luminosity. It also solves the problem of high turbulence in the region without signatures of the systematic outflow. Since the this mechanism of BLR formation seems universal, and there is no strong metalicity gradients in quasars up to high redshift, this also justifies the use Eq. 2.1 for distant quasars as a way to measure their luminosity distance and probe the dark energy distribution.

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