R-L Relation in Realistic FRADO Model

Mohammad-Hassan Naddaf1-2, Bożena Czerny1 and Ryszard Szczerba3

1. Center for Theoretical Physics, Lotnikow 32/46, 02–668 Warszawa, Poland
2. Nicolaus Copernicus Astronomical Center, Bartycka 18, 00–716 Warszawa, Poland
3. Nicolaus Copernicus Astronomical Center, Rabianska 8, 87–100 Torun, Poland

In Failed Radiatively Accelerated Dusty Outflow (FRADO) model which provides the source of material above the accretion disk (AD) as an option to explain the formation mechanism of Broad Line Region (BLR) in AGNs, the BLR inner radius ($\text{BLR}_{\text{in}}$ hereafter) is set by the condition that the dust evaporates immediately upon departure from the AD surface. On the other hand, the location of BLR clouds obtained observationally via reverberation mapping shows some scaling with the source luminosity, so-called RL relation. We assume $\text{BLR}_{\text{in}}$ to be the location of BLR clouds, then using a realistic expression for the radiation pressure of an AD, and having included the proper values of dust opacity, and shielding effect as well, we report our numerical results on calculation of $\text{BLR}_{\text{in}}$ based on FRADO model. We investigate how it scales with monochromatic luminosity at 5100Å for a grid of blackhole masses and Eddington ratios to compare along with the FRADO analytically predicted RL directly to observational data.

1 Introduction

Active galaxies can be used to test cosmological models due to RL relation. This location can be determined observationally from the time delay of the line emission with respect to continuum. The RL relation is usually calibrated for low redshift sources, assuming standard cosmology. However, FRADO model considering the fact that dust can exist in outer parts of AD (Dong et al., 2008), allows to calculate RL relation directly from the theory (Czerny & Hryniewicz, 2011). The 1-D analytical form of the model has been developed (Czerny et al., 2017). In the present numerical work, we aim at a realistic 3-D picture of the model to compare to analytical model and observational data.

2 $\text{BLR}_{\text{in}}$ in FRADO Model

The analytical model yields the onset of BLR simply by setting the effective temperature in a Shakura-Sunyaev AD equal to the dust sublimation temperature $T_{\text{sub}}$

$$\text{BLR}_{\text{in}} = \left( \frac{3GM_{\text{BH}} \dot{m} \dot{M}_{\text{Edd}}}{8\pi\sigma_B T_{\text{sub}}^4} \right)^{1/3}$$

(1)

where $M_{\text{BH}}$, $\dot{m}$, and $\dot{M}_{\text{Edd}}$ are blackhole mass, dimensionless accretion rate, and Eddington accretion rate, respectively. Approximating the monochromatic luminosity of AD at 5100Å for low mass sources (Czerny & Hryniewicz, 2011)

$$\log \left( \frac{L_{5100}}{10^{44} \text{ erg/s}} \right) = \frac{2}{3} \log(M_{\text{BH}} \dot{m} \dot{M}_{\text{Edd}}) + \log \cos i - 39.882$$

(2)
where \(i\) is the viewing angle, and combining with equation 1, one can find an interesting analytical RL relation which is independent of \(M_{\text{BH}}\), \(\dot{m}\), and \(\dot{M}_{\text{Edd}}\)

\[
\log \left( \frac{L_{\text{BLR}}}{10^{44}\text{erg/s}} \right) = \frac{1}{2} \log \left( \frac{L_{5100}}{10^{44}\text{erg/s}} \right) - \frac{4}{3} \log T_{\text{sub}} - \frac{1}{2} \log \cos i + 5.2436
\]

In 3-D picture, unlike the 1-D model we consider the radiation acting on dust is coming from whole AD radii. However, it can be argued that the radiation from AD is partly shielded due to either inner failed Compton-driven wind or cold material forming at the edge between the inner hot ADAF and a cold disk; otherwise too intense radiation from central region of AD causes too early dust evaporation within a large range of AD radii. So we incorporate the effect of shielding into the computations via our Patch-Model in which we assume that the radiation only comes from a small patch of the disk whose radius (\(s\)) is linearly proportional to the actual height (\(H\)) of the clump from the disk surface (\(s = \alpha H\)). The patch is always centered at a radius where the clump is flying above and increases in size as the cloud goes up. The energy absorbed by dust in our model is given by

\[
Q_{\text{abs}} = \int_{\lambda_i}^{\lambda_f} \int_{\text{patch}} f(r, M_{\text{BH}}, \dot{m}, K_{\text{abs}}(\lambda), T_{\text{eff}}(R), R, \varphi, \lambda, C) \, da \, d\lambda
\]

where \(r\) is the position vector of the clump in cylindrical coordinates in which the blackhole is at the origin, and \(z = 0\) corresponds to equatorial plane of AD, \(K_{\text{abs}}\) is dust absorption opacity as a function of wavelength, \(T_{\text{eff}}(R)\) is the effective temperature of S-S AD as a function of radius which is assumed to radiate locally at a given radius as a blackbody, \(R\) and \(\varphi\) indicate the location of infinitesimal surface areas of AD in polar coordinates, and \(C\) is some fixed factors and physical constants. We assume dust instantly emits the absorbed irradiated energy in the form of blackbody radiation. Once \(Q_{\text{abs}}\) exceeds \(Q_{\text{emit}}(T_{\text{sub}})\) dust gets immediately sublimated.

### 3 Numerical Setup & Results

We consider the dust content of BLR to follow the MRN dust model (Mathis et al., 1977) consisting of silicate and graphite, for which the mean absorption cross-section per dust mass (equivalent to dust opacity) is computed using MCDRT (Szcerba et al., 1997) and KOSMA–\(\tau\) PDR (Röllig et al., 2013) codes. Dust sublimation temperature is set to be 1500 K. The proportionality constant (\(\alpha\)) in Patch-Model is taken to be 1.5. A range of \(M_{\text{BH}} = [10^7, 10^8, 10^9]M_\odot\), and \(\dot{m} = [0.01, 0.1, 1]\) (for accretion efficiency of 0.1) is chosen as the model grid.

For each pair of \((M_{\text{BH}}, \dot{m})\) in our grid we compute the sublimation geometrical location above which dust cannot survive irradiation. Having the disk thickness computed using a numerical code (Czerny et al., 2016; Rożańska et al., 1999) which includes all opacities important at large disk radii, we find the crossing radius of the sublimation surface with the disk surface to be BLR_in. Finally, setting the viewing angle to be zero (faced-on disk) for simplicity, the results are plotted against the numerically computed values of \(L_{5100}\) (Czerny et al., 2003) in the left-panel of figure 1 and in the right panel a sample of observational data is provided (Martínez-Aldama et al., 2019).
Fig. 1: RL relation from numerical model (left) vs. observational sample (right).

4 Conclusion

The FRADO predicted BLR\textsubscript{in}-based RL relations are located below the expected RL from Bentz et al. (2013), which is for low redshift sources. However, they look interestingly more consistent with the recent BLR size measurements for high Eddington ratio sources, and especially the numerically predicted RL relations (shown by solid black lines in figure 1) follow the same slope as Bentz et al. (2013). Moreover, the model predicts that the real BLR is extended, so the realistic time delays from the entire BLR will be longer. In the future we will include this effect.

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