Filling a SMBH accretion disk atmosphere

at small and intermediate radii

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The medium above an accretion disk is highly diluted. It often contains hot and cold phases, permeated by radiation and magnetic fields, but an efficient mechanism to deliver particles and dust grains into the accretion disk atmosphere is still an open question. We discuss an interplay of different scenarios, where the material is elevated from the plane of an equatorial accretion disk into the corona near a supermassive black hole (SMBH). In particular: (i) radiatively driven acceleration by incident photons emerging from the disk, which can levitate the dust and help filling the Broad Line Region at radius about a few $\times 10^2$–$10^3 R_g$ [1–3]; and (ii) an electromagnetically induced transport of electrically charged particles and dust [4, 5].

1. Introduction

Radio-quiet Active Galactic Nuclei (AGN) frequently exhibit Broad Emission Lines in IR/optical/UV bands. These lines are thought to originate from the centrally irradiated Broad Line Region (BLR) clouds moving above an underlying accretion disk or a torus. Their medium is composed of complex plasma with gas and dust phases at different states of mutual contact at different radii (typically, a fraction of parsec) from the central supermassive black hole, SMBH (mass $M_\bullet \simeq 10^6$–$10^8 M_\odot$, gravitational radius $R_g \equiv GM_\bullet/c^2 \simeq 1.48 \times 10^{12} M_7$ cm, where M_7 is the mass of the black hole in units of 10^7 solar masses). Other components interact with each other, namely: the Nuclear Star Cluster (NSC) is present and it contributes to radiative and mechanical heating of the interstellar medium (radius $R_{\rm NSC}$ is typically of a few pc, mass $M_{\rm NSC}$ comparable to or greater than that of SMBH); also, magnetic fields are present with both a small-scale (turbulent, $\ell \approx R_g$) and a large-scale (organized, $\ell \gg R_g$) components which influence motion and acceleration of charged particles and plasma.

Existence of BLR clouds high above the accretion disk poses a challenge to the models: a persistent mechanism must operate in order to supply the gas/dust into the disk atmosphere and maintain it against gravity, which tends to bring the dispersed material into the equatorial plane. Several possibilities have been explored: based on radiation pressure from an underlying accretion disk and stars of the NSC, effects of stellar winds and mechanical action by NSC stars passing across the accretion disk, and electromagnetic levitation of electrically charged dust grains. It seems that a single explanation does not capture varied properties of BLR clouds; quite likely, a mutual interplay of different processes has to be considered. Here we summarize our recent work and we examine several aspects of the problem in which the dust phase plays and important role.

2. Broad Line Region as Failed Radiatively Accelerated Dusty Outflow

At small radius near the central SMBH, dynamics of BLR clouds is dominated by the Keplerian motion in strong gravitational field. At small height z above the accretion disk, local radiation field $F_{\rm rad}$ contributes significantly to the BLR acceleration in the vertical direction. To start with a simple illustration (standard disk accretion onto a SMBH), in the absence of other forces the cloud velocity in the vertical direction perpendicular to the disk plane is obtained by solving [2, 6]

$$\frac{dv}{dt} = -\frac{GM_\bullet z}{r^3} + \frac{\kappa F_{rad}}{c}, \qquad F_{\rm rad} = \frac{3GM_\bullet \dot{M}_\bullet}{8\pi r^3}, \tag{1}$$

where $\dot{M}_\bullet$ is the accretion rate and κ is mean opacity. A more elaborate description of the opacity allows us to study the mechanism of radiation supported outflows (such the case of a line-driven dusty wind), where the physical conditions and, thus, optical thickness vary across the medium.

Failed Radiatively Accelerated Dusty Outflow (FRADO) is proposed as the mechanism producing BLR [1–3]. Near the black hole and high above the disk plane the plasma becomes exposed to an enhanced irradiation by the central source. This leads to the destruction of the dust. Upward acceleration of the dust is terminated either by the grain sublimation and disappearance, or the wind fails and the dust disappears (Fig. 1). The phases of motion in the direction upward from vs. downward toward the disk plane are asymmetric with respect to each other. In the most simple form of our scenario, clouds are launched with zero vertical speed from the disk surface; they fall back with a non-zero speed and hit the disk surface, so the net effect imitates some outflow even if although the material does not reach infinite distance.

Clouds are viewed by a distant observer at the inclination angle i with respect to the symmetry axis (defined by the common equatorial plane of the inner accretion disk a the outer dusty torus, as in the standard Unified Scheme of AGN). BLR clouds reprocess the incident radiation, including the effects of self-obscuration. Fraction of the incident flux from the central SMBH source and surrounding NSC stars is transformed into the spectral line emission [7, 8] (see Figs. 2–3).

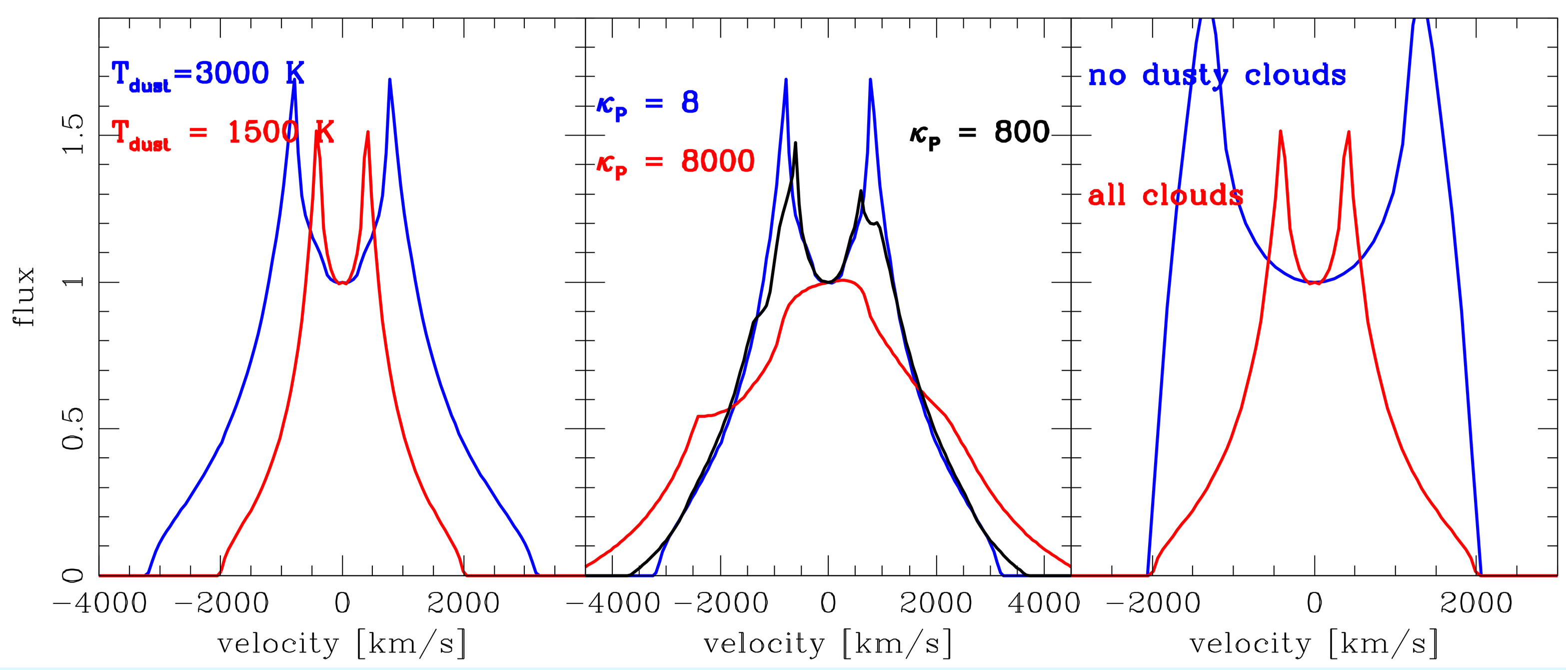

Fig. 2. The predicted emission-line profiles as function of the model parameters for several typical values, depending on the model assumptions: the dust sublimation temperature (left panel), the Planck opacity (middle panel), and the dust not affecting the line emissivity (right panel). The parameters of the reference model are: the black hole mass $M_\bullet = 10^7 M_\odot$, the accretion rate $\dot{M}_\bullet/M_{\rm Edd} = 0.6$, the inclination angle $i = 45$ deg, the dust sublimation temperature $T_{\rm dust} = 3000$ K. See ref. [3] for further details.

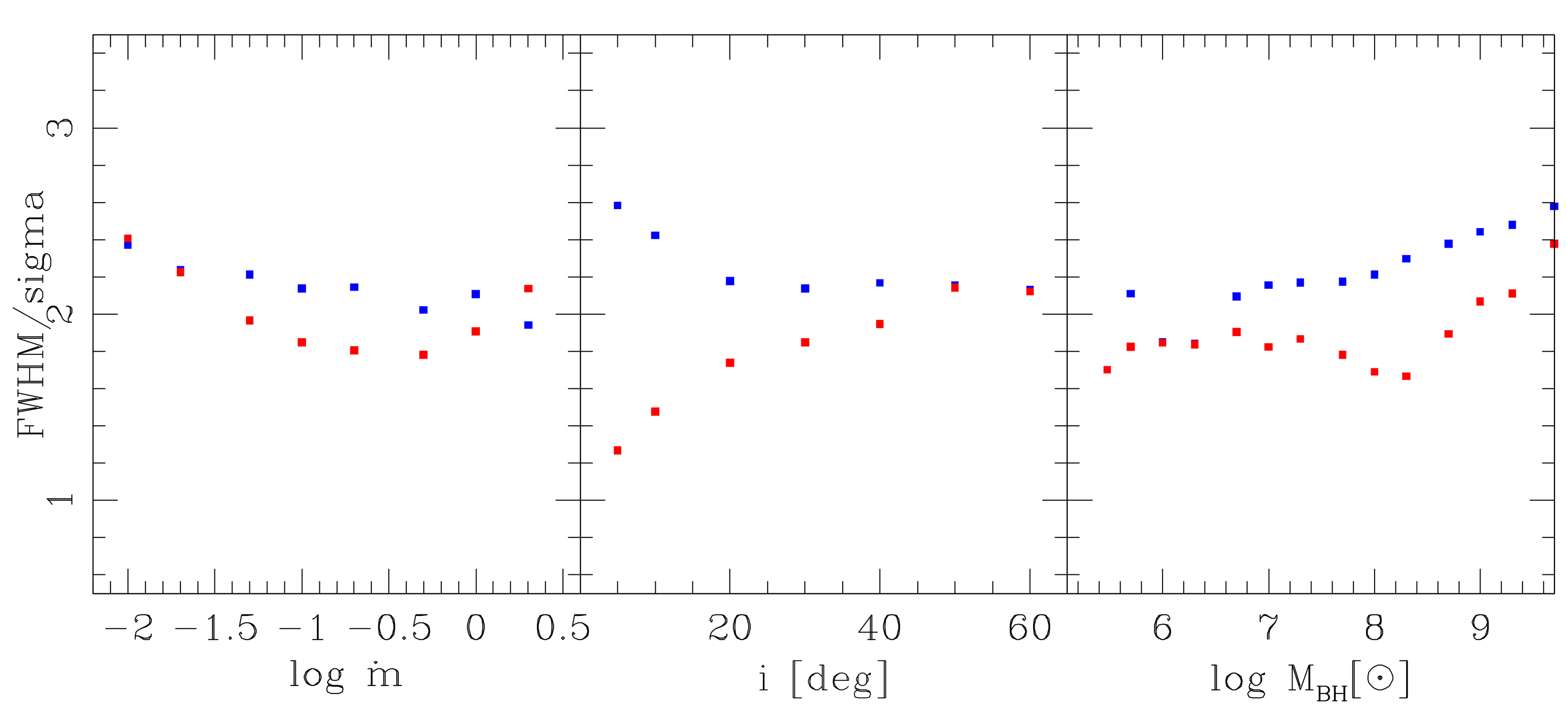

Fig. 3. The FRADO model contains the information about FWHM of the line and the virial factor $h_{\rm vir}$. We find that the values agree well with the typical numbers reported in observational samples. Here we plot the predicted ratio of FWHM to the dispersion measure σ as a function of the dimensionless Eddington accretion rate (left), the viewing angle (middle), and the black hole mass (right). We set the fixed values of the parameters at $M_\bullet = 3 \times 10^7 M_\odot$ and $\dot{m} = \dot{M}_\bullet/\dot{M}_{\rm Edd} = 0.1$. We selected opacity $\kappa_P = 8$ cm^2/g (blue points) and $\kappa_P = 800$ cm^2/g (red points), respectively [3].

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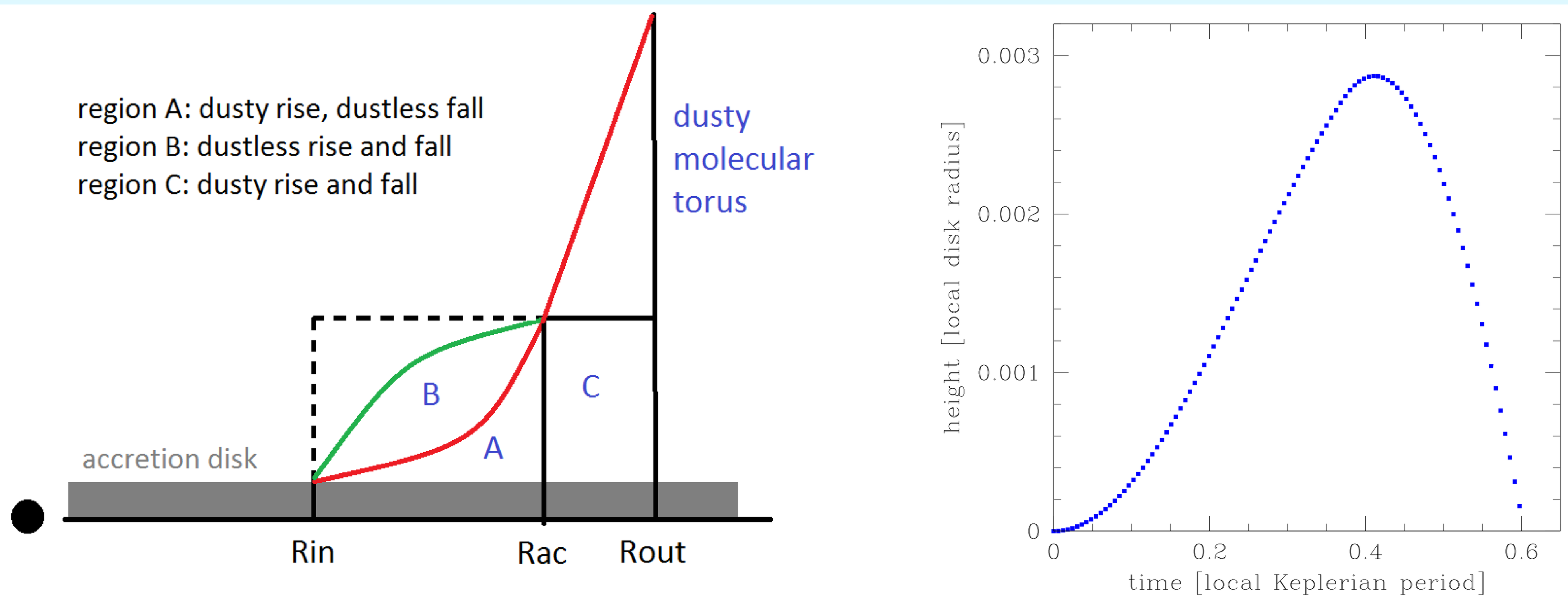

Fig. 1. Left panel: the mechanism of the rise and fall of the Broad Line Region clouds is shown schematically in a poloidal section across an accretion disk (SMBH is indicated by the black circle in the origin). The inner parts of BLR are filled with a mixture of dusty and dust-less clouds; the outer region is dominated by dusty clouds. Right panel: the cloud motion exhibits asymmetry in the rise/fall phases due to the interplay between the radiation pressure force and the gradual dust sublimation of irradiated and heated grains [2].

3. Open questions, alternatives and annoyances

The above-described model of radiatively accelerated plasma/dust clouds does not contain, in its basic form, any free parameters. Still, it reproduces the position of the BLR consistent with the results from the reverberation methods, and it correctly predicts the typical ratios of the optical spectral line FWHM. Within this frame, using the FRADO scenario, we can achieve a satisfactory explanation of the position of the inner edge of the BLR in relation to the dust sublimation radius. We also calculated the expected time delays between the disk continuum determined at 5100 Å and the line emission coming from the BLR; the flux of the Mg II and Hβ lines (Low Ionization Lines) is recovered quite well, and the model even reproduces the line asymmetry, which is usually modelled as another independent component.

Despite the encouraging agreement of the above discussed dusty wind scenario, its basic formulation does not seem to lift the material high enough to get it exposed to the illumination from the central source as needed. An efficient rise of the material takes place only if we increase the dust IR opacity to an artificially high value. The question arises whether the dust-driven wind can form at all, due to the counter-acting influence of vertical gravity that rises with the distance, or the adopted scenario might be too simplistic. The main difficulty seems to be to reach efficient elevation of the clouds to rise to sufficiently high latitude, as expected in BLR. We can identify several aspects of the model that need to be refined. Also, a closer look reveals that the model has a difficulty to reproduce the observed Lorentzian tail on the red wing of the Mg II line with sufficient accuracy.

Firstly, the description of the BLR cloud dynamics used here is purely local; the initial velocity of the material is set to be zero in the calculations, and the driving force arises just from the underlying accretion disk. Only after the initial rise, the matter becomes exposed to the irradiation from the central SMBH source. Thus, not reaching higher elevations is a problem for our description of opacity.

Secondly, our computations of the disk structure cannot cover the entire BLR because the effects of the self-gravitation become too strong to substantiate the use of the standard (marginally-self-gravitating) approximation [2]. Indeed, the self-gravity sets in once the Toomre parameter becomes less than unity; this transition occurs typically within BLR. For large SMBHs the self-gravity radius is significantly smaller than the BLR radius, while it comes out opposite for small $M_\bullet$; despite that, we do not see any significant difference between the BLR properties for small vs. large black hole masses at the same accretion rate.

Thirdly, the stellar population should play a significant role in creating and/or maintaining the BLR clouds, either by starburst activity or by supplying the material via direct encounters with an accretion disk/torus [9–11]. Let us note, that our discussion in the present work has been constrained to the purely Newtonian framework. This assumption is sufficiently accurate at distance exceeding tens and hundreds gravitational radii from the central black hole, however, it may be necessary to include effects of general relativity in the innermost part of the BLR. The phenomenon of star–disk interaction operates in the system even if it is disturbed by the relativistic pericentre shift and by the gravity of the nuclear cluster. The presence of a gaseous disk of a non-zero mass helps to drag stars to the black hole, thereby feeding the centre and simultaneously providing material that sustains and replenishes both the disk and the BLR. Disruption of stellar bodies and subsequent accretion of the remnant gas are among likely mechanisms feeding supermassive black holes that are embedded in a dense nuclear star cluster.

Other alternatives for the accretion disk winds as the origin of BLR phenomenon have been discusses in the literature: they are magnetic winds and line-drive winds. Indeed, the disk atmosphere is likely strongly magnetized; this can play an important role in BLR if the specific charge of plasma particles reaches non-negligible values [12] (the effect of dragging the large scale magnetic field from the interstellar medium towards the black hole is frequently considered in the context of jet formation). The environment in accretion disk atmosphere (complex plasma) is typically subjected to intense UV/X light. Consequently, the dominant process for charging dust particles within astrophysical plasmas is photoelectron emission in a competition with the collection of ambient electrons and ions. Then, charges are separated in the organised magnetic fields [4, 5], which thread the torus and elevate the electrically charged dust far above the disk plane, thus helping to alleviate the problem of dust not reaching sufficiently high latitudes.

4. Conclusions

The leading mechanims in the dynamics of BLR clouds are still an open question. We have considered various possibilities and discussed their advantages and problems. FRADO model is based on the effect of radiation pressure acting on a dusty disk atmosphere. In its basic formulation, the scenario depends only on the global parameters of an AGN, and so it has a great predictive power. Still, it appears that an astrophysically realistic description will have to incorporate additional ingredients, such as the effects of self-gravity, magnetic fields and dust charging processes.

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