Modeling line-driven disk wind for broad absorption lines of quasars

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Summary

We investigate the conditions that the line driven disk wind model reproduces the BAL features.

We research the structure of the disk wind by using non-hydrodynamic calculations which are modified version of Risaliti & Elvis (2010) for wide range of the parameters of the black hole mass, the Eddington ratio, and the density of the wind-base. We calculate the ionization parameter, the velocity and the column density along the each viewing angle and compare with the X-ray observation of BAL quasars.

We find that the probability that the BAL is observed is large for large black hole mass and large Eddington ratio and additionally the BAL features are observed when we observe the line driven disk wind from large viewing angle. When the density of gas at the wind-base is the same as that of BELR, the disk wind model can reproduce BAL features. Our results support the new hypothesis that the wind-base is the BELR.

Method

Basic equations

Equation of motion

$$\frac{d\mathbf{v}}{dt} = -\frac{GM_{\rm BH}\mathbf{R}}{R^3} + \frac{GM_{\rm BH}r_0\mathbf{r}}{r^4} + \frac{\sigma_{\rm e}\mathbf{F}}{c} + M\frac{\sigma_{\rm e}\mathbf{F}}{c}$$

Force multiplier

$$M = M(\xi, t)$$

(Stevens & Kallman 1990)

We calculate the equation of motion in the cylindrical coordinate (r,ϕ,z)

$\mathbf{v}$: velocity of the fluid element
$\mathbf{R}$: point vector of the fluid element
G : gravity constant
$M_{\rm BH}$: black hole mass
$\sigma_{\rm e}$: mass-scattering coefficient for free electrons
c : speed of light
$\mathbf{F}$: radiative flux
ρ : density
n : number density

Mass conservation equation

$$\rho = \frac{\rho_0 v_0 r_0^2}{|v|r^2}$$

Energy equation

$$n^2(G_{\rm Compton} + G_{\rm X} - L_{\rm b,l}) = 0$$

$G_{\rm Compton}$: compton heating/cooling rate
$G_{\rm X}$: rate of X-ray photoionization heating and recombination cooling
$L_{\rm b,l}$: bremsstrahlung and line cooling

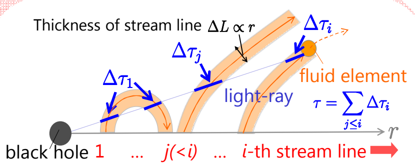
(Proga et al. 2000))

Radiation

UV: accreton disk
X : point source

$$F_{\rm UV,\theta} = F_{\rm UV,\theta,thin}$$
$$F_{\rm UV,R} = e^{-\tau_{\rm UV}} F_{\rm UV,R,thin}$$
$$F_{\rm X,R} = e^{-\tau_{\rm X}} F_{\rm X,R,thin}$$

* $\tau_{\rm UV}$: calculated considering electron scattering
* $\tau_{\rm X}$: calculated considering electron scattering and absorption
* UV source is accretion disk, but the optical depth of UV is measured from the origin.



We calculate the stream lines in order of the distance from the black hole. When we solve *i*-th stream line, we consider the extinction of the radiation via every inner stream lines of *j*-th (*j* < *i*) and the self-shielding by *i*-th flow.

Initial conditions/ parameters

Initial position, initial velocity, initial density

$$z_0 = 5R_{\rm S},\ r_0 = 20, 28, 36, \cdots 660R_{\rm S}$$

$$v_{r0} = 0,\ v_\phi = v_{\rm kepler},\ v_{z0} = 10^7{\rm cm\,s^{-1}}$$

(The other case of $v_{z0} = 10^6{\rm cm\,s^{-1}}$ is shown in Nomura et al. (2011) submitted to ApJ.)

$$\rho_0 = 10^{-14}{\rm g\,cm^{-3}}$$

(The other cases of $10^{-15}, 10^{-13}{\rm g\,cm^{-3}}$ are shown in Figure 4.)

Black hole mass & Eddington ratio

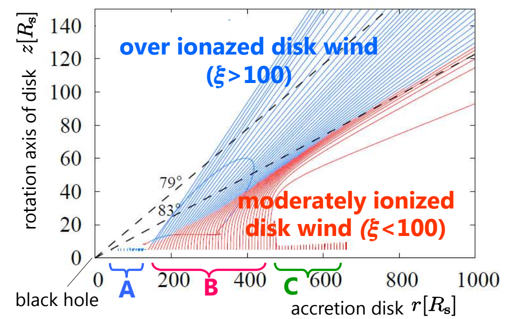
$$M_{\rm BH} = 10^7 - 10^9 M_\odot,\quad \epsilon = 0.1 - 0.9$$

Result(1)-Wind structure and BAL probability

Fig1. Wind structure

Wind structure for $\rho_0 = 10^{-14}{\rm g\,cm^{-3}},\ {\rm v}_0 = 10^7{\rm cm\,s^{-1}}, \epsilon = 0.5$ and $M_{\rm BH} = 10^7 M_\odot$

Trajectories (lines) and ionizing degree (color)



A: The gas is overionized and line force cannot work.

B: Line force works efficiently and the gas is accelerated.

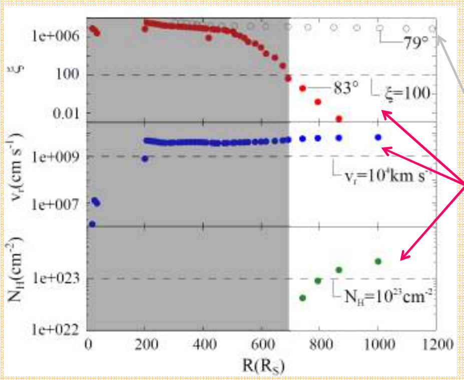
C: UV is obscured and not enough to accelerate the wind.

The disk wind with opening angle ~75° is launched from the limited region of ~100R$_{\rm S}$

Fig2. Distance dependence

Ionization parameter (top), velocity (middle) and column density (bottom) for θ=83°

Ionization parameter for θ=79° (open circles in top panel)



BAL conditions

(A) The outward velocity of the matter with ξ< 100 exceeds 10^4 kms^{-1}.

(B) The column density of the gas with ξ < 100 is over 10^{23} cm^{-2}.

If both conditions are satisfied, we recognize that the BAL features emerge in the spectra.

θ=79°: BAL conditions are not satisfied.

θ=83°: BAL conditions are satisfied.

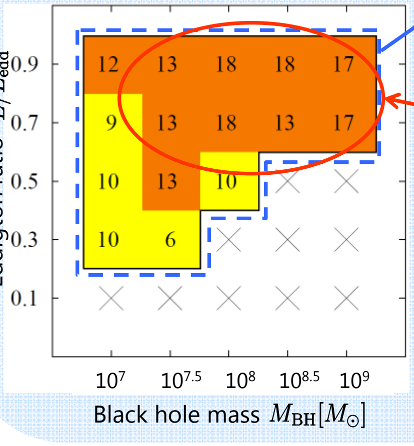
We find that the BAL conditions are satisfied if we observe the system at the viewing angle of $\theta \geq 82°$. Since we have $\Omega_{\rm BAL}$ = 4π cos(82°), the BAL probability is obtained as $\Omega_{\rm BAL}/4\pi \sim$ 10%.

Result(2)-Parameter dependence

Dependence on black hole mass and Eddington ratio

Fig3. BAL probability

BAL probability for $\rho_0 = 10^{-14}{\rm g\,cm^{-3}}$



$L/L_{\rm edd}$	10^7	$10^{7.5}$	10^8	$10^{8.5}$	10^9
0.9	12	13	18	18	17
0.7	9	13	18	13	17
0.5	10	13	10	×	×
0.3	10	6	×	×	×
0.1	×	×	×	×	×

The BAL features appear for larger Eddington ratio and smaller black hole mass.

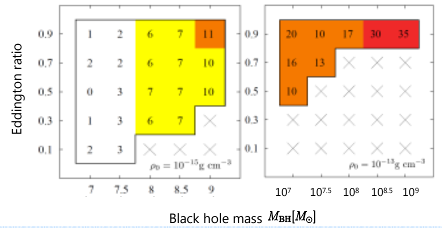
BALs are identified with high probability in quasars with massive black holes and higher Eddington ratio.

The dichotomy between BAL and non-BAL quasar is determined by not only viewing angle but also the black hole mass and Eddington ratio.

Dependence on initial density

Fig4. BAL probability for different initial density

BAL probability for $\rho_0 = 10^{-15}{\rm g\,cm^{-3}}$ (left) and $\rho_0 = 10^{-13}{\rm g\,cm^{-3}}$ (right)



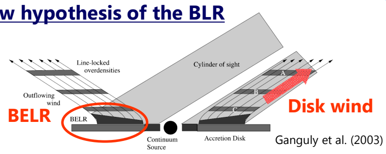
$\rho_0 = 10^{-15}{\rm g\,cm^{-3}}$:

Eddington ratio	7	7.5	8	8.5	9
0.9	1	2	6	7	11
0.7	2	2	6	7	10
0.5	0	3	7	7	10
0.3	1	3	6	7	×
0.1	2	3	×	×	×

$\rho_0 = 10^{-13}{\rm g\,cm^{-3}}$:

Eddington ratio	10^7	$10^{7.5}$	10^8	$10^{8.5}$	10^9
0.9	20	10	17	30	35
0.7	16	13	×	×	×
0.5	10	×	×	×	×
0.3	×	×	×	×	×
0.1	×	×	×	×	×

New hypothesis of the BLR



Ganguly et al. (2003)

Ganguly et al. (2003) propose then new hypothesis that the wind-base is the broad emission line region (BELR).

Such hypothesis is supported by the observation that the disk wind seems to partially cover the BELRs (Arav et al. 1999).

The wind-regime becomes wide but the BAL probability decreases as the initial density goes down. In contrast, the BAL probability goes up but the wind-regime shrinks with an increase with the initial density.

The observation of the BAL is well explained when we set the initial density to be ～10^{-14}g cm^{-3}. The gas density of BLR is also ～ 10^{-14}g cm^{-3} and rotational velocity at the base (> 10^{8}cm s^{-1}) of the disk wind can explain the width of the emission line.

Our results support the new hypothesis that the wind-base emits the broad emission lines (Ganguly et al. 2003).

References

1) Arav et al. 1999, ApJ, 516, 27
2) Castor et al. 1975, ApJ, 195, 157
3) Ganguly et al 2003, ApJ, 598, 922
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6) Stevens & Kallman 1990, ApJ, 365, 321

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