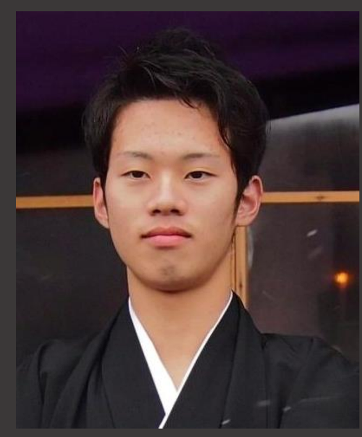
General relativistic radiation magnetohydrodynamics simulations of super-critical accretion disks around Kerr black holes



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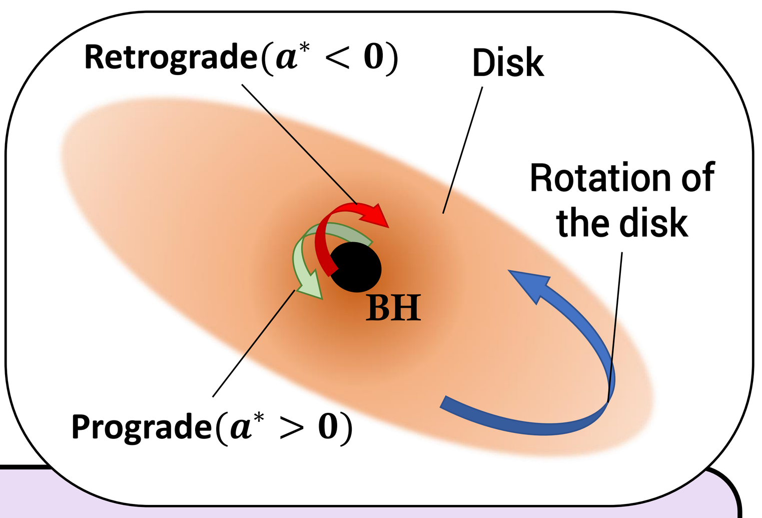
Introduction

Super-critical accretion disks are thought to be the engine of the very luminous, compact objects, e.g., ultra luminous X-ray sources, narrow-line Seyfert galaxies, tidal disruption events, and so on. However, the dependence of the outflow on the black hole spin parameter (a^*) is not well understood. We perform 2.5-dimensional general relativistic radiation magnetohydrodynamics (GRRMHD) simulations to investigate the dependence of luminosity and jet power on the spin parameter in super-critical accretion disks.



Basic eq. & Methods

- Mass conservation
$$(\rho u^\nu)_{;\nu} = 0$$
- The energy-momentum conservation for magnetofluids
$$T^\nu_{\mu\ ;\nu} = G_\mu$$
- The energy-momentum tensor for radiation field
$$R^\nu_{\mu\ ;\nu} = -G_\mu$$
- Induction equation
$$\partial_t(\sqrt{-g}B^i) = [\sqrt{-g}(B^i v^j - B^j v^i)]$$
- The energy momentum tensor for magnetofluids
$$T^{\mu\nu} = (\rho + e + p_g + 2p_m)u^\mu u^\nu + (p_g + p_m)g^{\mu\nu} - b^\mu b^\nu$$
- The energy momentum tensor for radiation
$$R^{\mu\nu} = p_{rad}(4u^\mu_{rad}u^\nu_{rad} + g^{\mu\nu})$$

The radiation equation is based on a moment formalism with applying a **M-1 closure**.

Note.
c : Light speed ($c = 1$)
ρ : Mass density
u^μ : Four velocity
$T^{\mu\nu}$: Energy momentum tensor
G^μ : Radiation four force
g : Determinant of $g_{\mu\nu}$ **(Kerr-schild metric)**
B^i : Magnetic field
v^i : Three velocity
e : Internal energy
p_g : Gas pressure
p_m : Magnetic pressure
b^μ : Magnetic four vector
p_{rad} : Radiation pressure
u^μ_{rad} : Radiation four velocity

2.5D GRRMHD simulations (Takahashi et al. 2016)

Models.
- Axis symmetric.
- Calculation box size : $r = [0.96r_H, 245]r_g, \theta = [0, \pi]$ (r_H:Event horizon , r_g: Gravitational radius).
- Grid points : $(N_r, N_\theta, N_\phi) = (264,264,1)$
- BH mass : M = $10M_\odot$
- BH spin : $-0.7 < a^* < 0.7$ (9 parameters)
- Electron-scattering(comptonization) + Free-free absorption

Initial condition
- Set the rotational equilibrium torus.
- Maximum density of initial torus. $\rho_0 = 1.4 \times 10^{-2}$ [g cm^{-3}]
- Weak poloidal magnetic fields. Plasma beta : $\beta = 100$

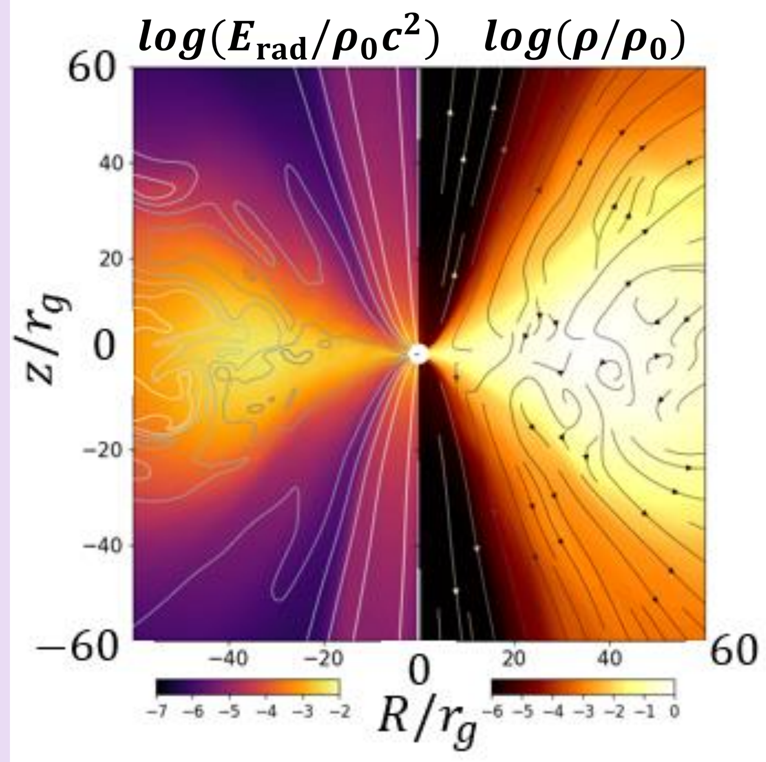


Fig.1 Quasi-steady structure of accretion disks and outflows. Color shows radiation Energy density (left),mass density(right). Vectors show stream-lines, and gray curves show magnetic field lines.

Results of spin parameter dependence.

1. Mass inflow rate $\dot{M}_{in}$. (Fig.2,3)

$$\dot{M}_{in}(a^* = 0.7) < \dot{M}_{in}(a^* = 0) < \dot{M}_{in}(a^* = -0.7)$$

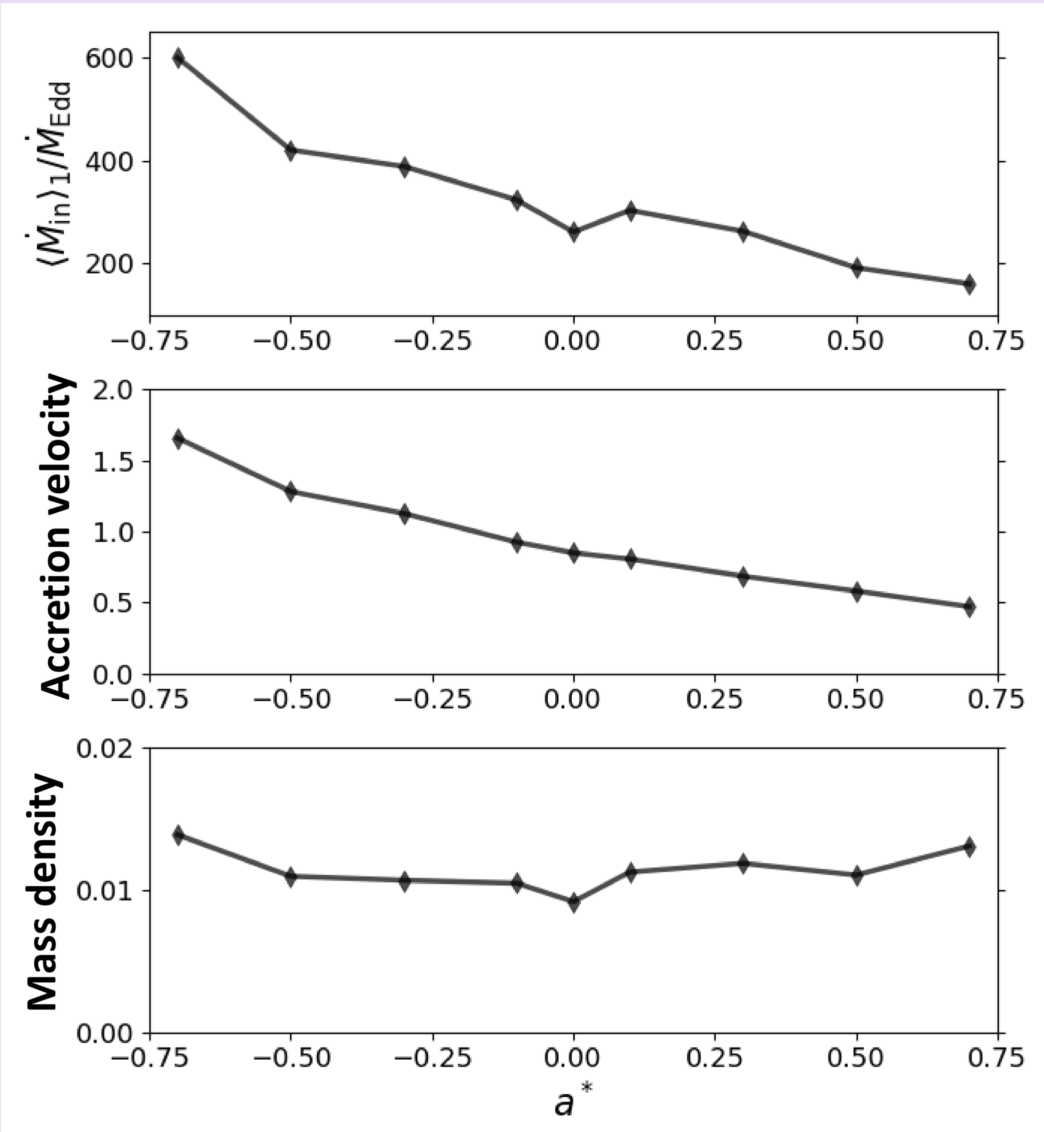


Fig.2 BH spin dependence of Mass inflow rate(top), accretion velocity(middle) and mass density(bottom).

The mass inflow rate is three times higher for case $a^* = -0.7$ than for case $a^* = 0.7$.
⇒
It is caused by the difference of the accretion velocity.

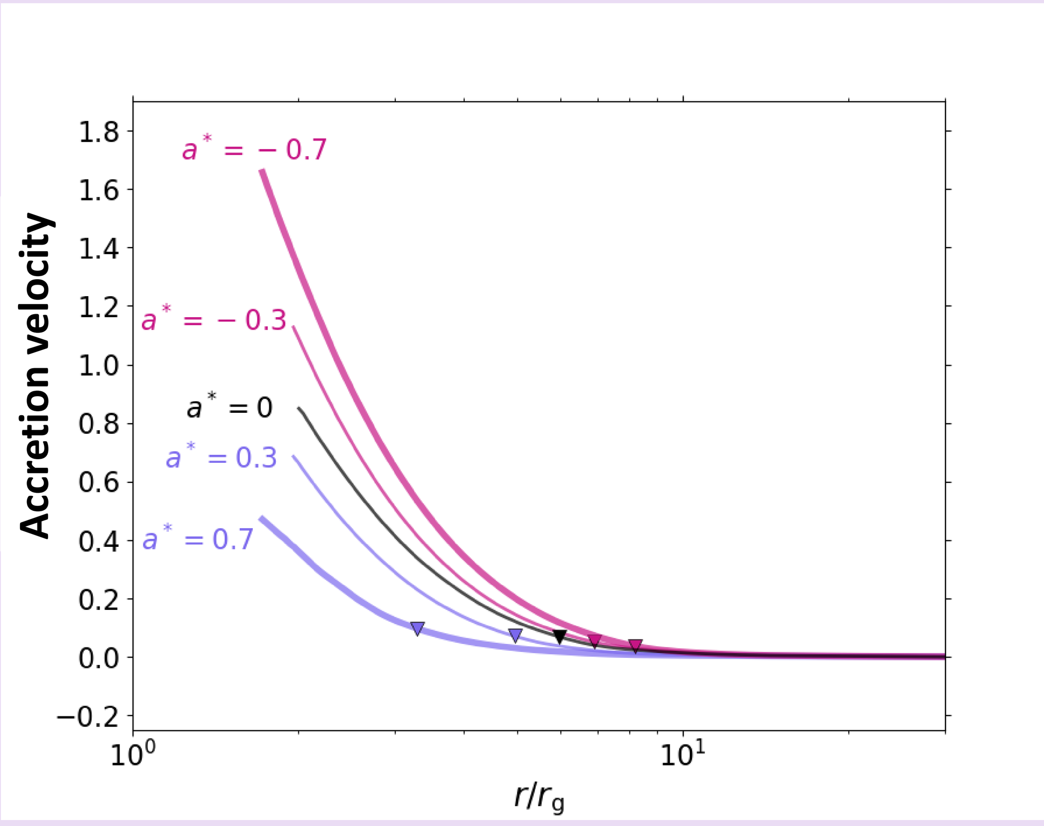


Fig.3 Radial distribution of accretion velocity. Marker shows ISCO radius. (The curve ends at EH.)

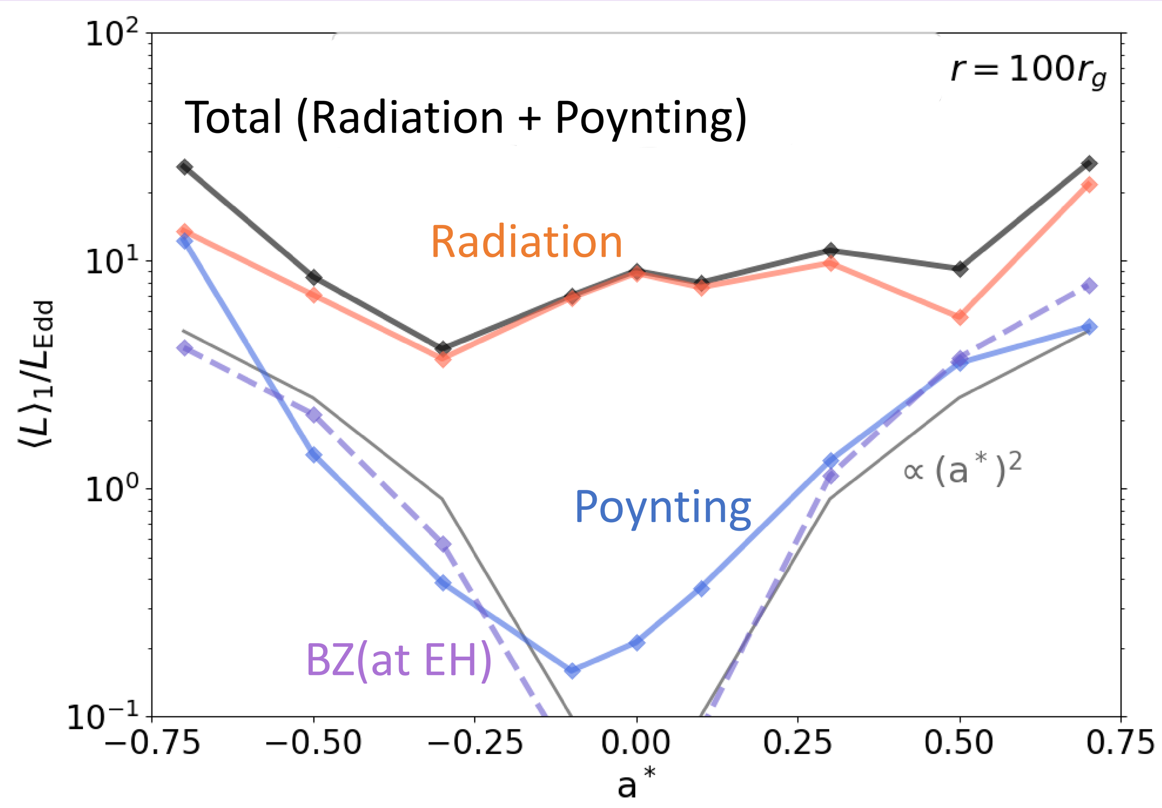
Consideration
In the region inside the inner most stable orbit radius (ISCO), the gas accretion velocity increases as the gas approaches the Event Horizon.
↓ ↓ ↓
Since the ISCO radius decreases as a^* increases, the accretion velocity decreases as a^* increases.

This suggests that the growth of BHs is faster in retrograde BHs.

2. Luminosity in the jet region. (Fig. 4)

The Luminosity of the Jet region increases as $|a^*|$ increases.

- The total luminosity is much larger than the luminosity by the Blandford-Znajek (BZ) mechanism. Therefore, the main energy source is the disk.
- As $|a^*|$ increases, total luminosity and BZ luminosity are increasing. The BZ mechanism contributes to the $|a^*|$ dependence of total luminosity.
- The radiation luminosity, which is larger than the luminosity via the poynting flux, is ~20,10 and $15L_{Edd}$ for $a^* = 0.7$,0 and -0.7.



The jet region:
Bernoulli parameter
$B_e > 0.05$
(Sadowski et al. 2013.)

Fig.4. Luminosity calculated in the Jet region(at r=100rg)

Note.
L_{Edd} : Eddington luminosity

Fluxes
Radiative flux
$$R^i_t = 4p_{rad}\, u_{t\, rad} u^i_{rad}$$
Poynting flux
$$M^i_t = b^2 u_t u^i - b_t b^i$$

Extraction of energy by BZ mechanism.
(Mckinney & Gammie 2004)

BZ poynting flux
$$F_{BZ}\Big|_{r_H} = 2(B^r)^2 \omega r_H(\Omega_H - \omega)\sin^2\theta$$
ω : Angular velocity of magnetic field.

$\Omega_H = (\frac{a^*}{2r_H})$: Angular velocity of BH spin.

Conclusions

- The mass inflow rate is larger for retrograde BH. The main cause is the accretion velocity induced by the difference in ISCO.
- The main energy source for the jet is the disk, but the BZ mechanism contributes to the $|a^*|$ dependence.
- Radiation Luminosity is maximum in jet region.