Energy outflow efficiency of the supercritical accretion disks around Kerr-black holes by General relativistic radiation-MHD simulations

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Introduction

Supercritical accretion disks with luminosities exceeding the Eddington luminosity $L_{\rm Edd}$ are thought to appear when the mass accretion rate exceeds the Eddington limit. Ultra-luminous X-ray sources (ULXs) are compact X-ray sources with X-ray luminosities above 10^{39} [erg/s], but their energy sources are not yet understood. One possibility is supercritical accretion onto a stellar mass black hole (BH). Previous studies of supercritical accretion disks have focused on non-rotating BH surroundings, and the effects of BH rotation have not been fully investigated. As the BH rotates, the available gravitational energy changes because the inner radius of the disk changes. In addition, extraction of the rotational energy of the BH via the magnetic field can also occur (Blandford & Znajek 1977: BZ). These effects may affect the structure of the supercritical accretion disk, the radiation intensity, and the power of the Jet.

Basic eq. & Methods

- The mass conservation eq.

$$(\rho u^{\nu})_{;\nu} = 0$$

- The energy momentum conservation for magnetofluid.

$$T^{\nu}_{\mu;\nu} = G_{\mu}$$

- The energy momentum conservation for radiation.

$$R^{\nu}_{\mu;\nu} = -G_{\mu}$$

- The induction eq.

$$\partial_t(\sqrt{-g}B^i) = [\sqrt{-g}(B^i v^j - B^j v^i)]$$

-- The energy momentum tensor for magnetofluid.

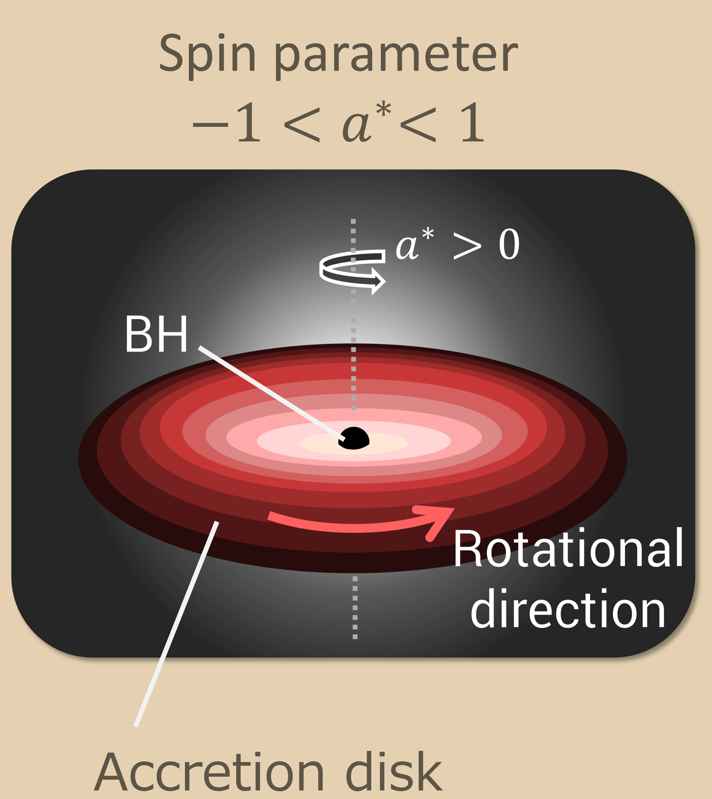
$$T^{\mu\nu} = K^{\mu\nu} + M^{\mu\nu}$$
$$K^{\mu\nu} = (\rho + e + p_{\rm g})u^{\mu}u^{\nu} + p_{\rm g}g^{\mu\nu}$$
$$M^{\mu\nu} = 2p_{\rm m}u^{\mu}u^{\nu} + p_{\rm m}g^{\mu\nu} - b^{\mu}b^{\nu}$$

-- The energy momentum tensor for Radiation (M1 closure).

$$R^{\mu\nu} = p_{\rm rad}(4u^{\mu}_{\rm rad}u^{\nu}_{\rm rad} + g^{\mu\nu})$$

Note.

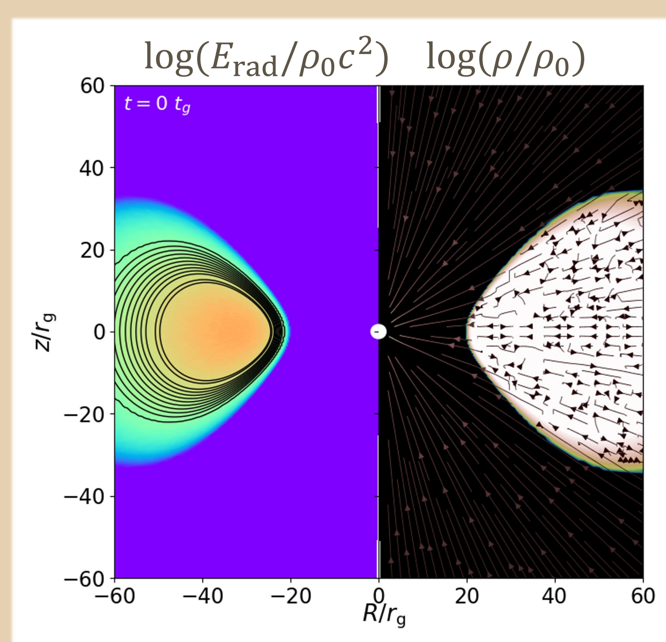
- c : Light speed ($c = 1$)
- ρ : Mass density
- u^{μ} : Four velocity
- G^{μ} : Radiation four force
- g : Determinant of $g_{\mu\nu}$ (**Kerr-schild metric**)
- B^i : Magnetic field
- v^i : Three velocity
- e : Internal energy
- $p_{\rm g}$: Gas pressure
- $p_{\rm m}$: Magnetic pressure
- b^{μ} : Magnetic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



2.5D General relativistic radiation-MHD (GR-RMHD) Simulation (Takahashi et al. 2016)

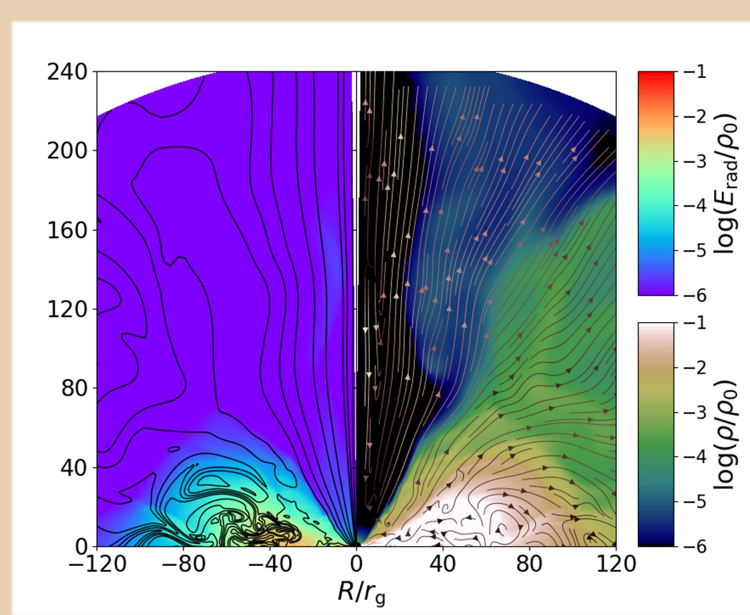
■Model

- Axis symmetric
- Simulation box size : $r = [r_{\rm H}, 250]r_{\rm g}$, $\theta = [0, \pi]$ ($r_{\rm H}$: Event Horizon , $r_{\rm g}$: Gravitational radius).
- Grid: $(N_r, N_\theta, N_\phi) = (264,264,1)$
- BH mass: $M = 10M_{\odot}$
- BH spin: $a^* = 0, \pm0.3, \pm0.5, \pm0.7, \pm0.9$
- Thomson-scattering (Compton-scattering) ＋Free-Free absorption.



■Initial condition

- Equilibrium torus
- Initial maximum density $\rho_0 = 1.4\times10^{-2}$ [g cm^{-3}]
- Poloidal magnetic field
- Plasma beta: $\beta_{\rm ini} = 100$ Standard and Normal evolution (SANE)



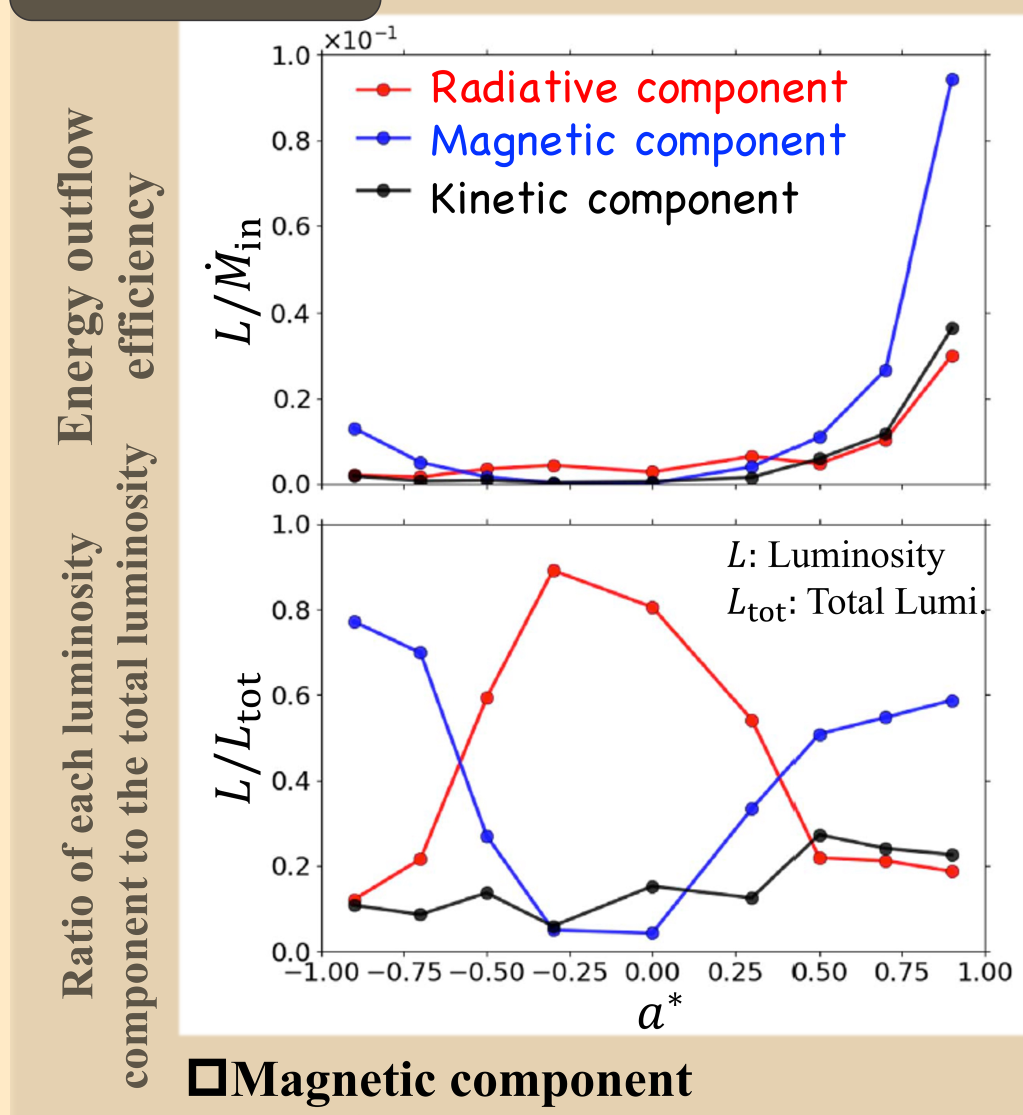
■Overview of quasi-steady state

- Mass accretion rate $\dot{M}_{\rm in} \approx 100L_{\rm Edd}$
- Formation of outflow: Wind + Jet

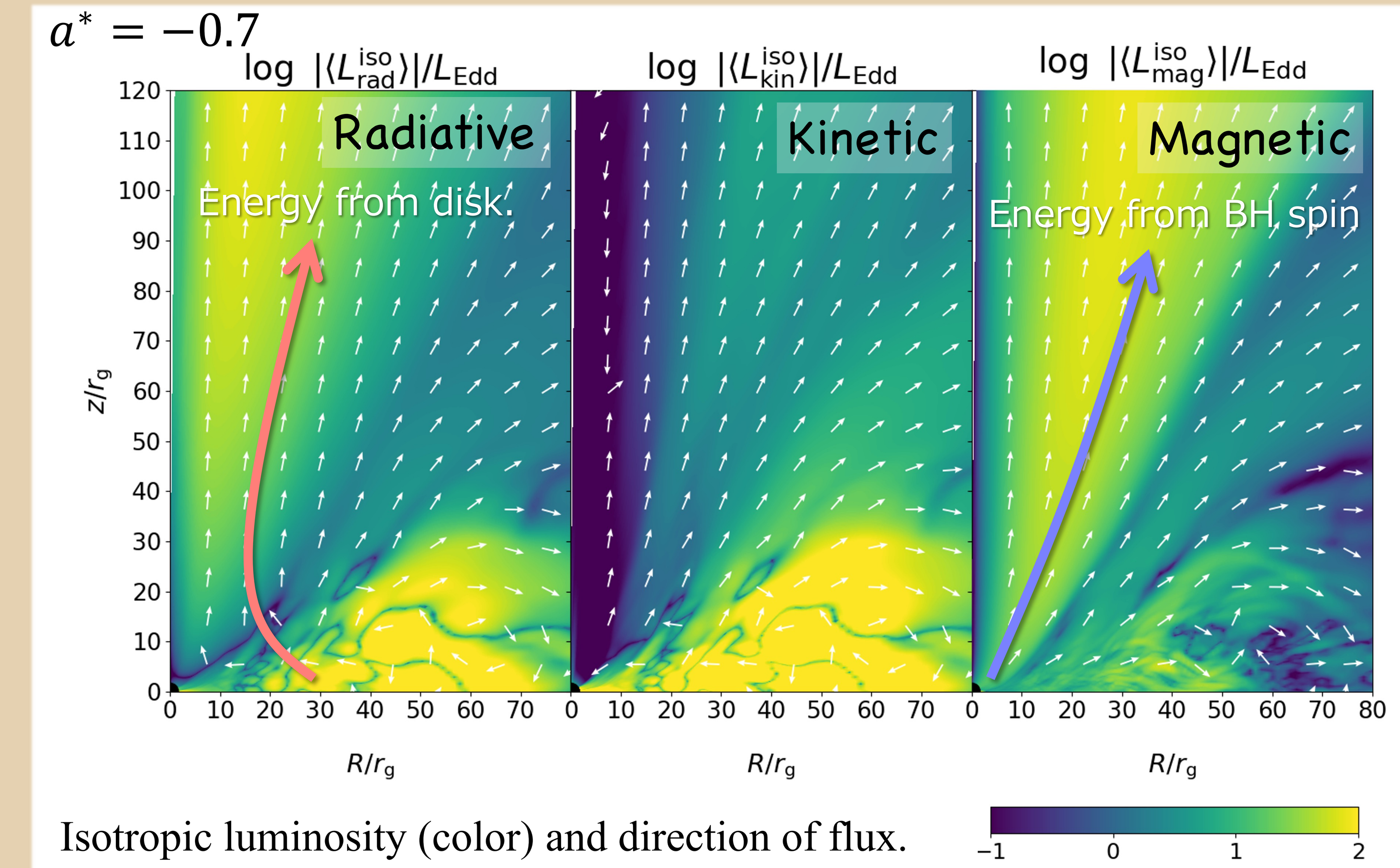
Left panel: Radiative energy density (color) and magnetic fields.
Right panel: Rest mass density (color) and streamlines.

Results

■BH spin dependence for each component of energy outflow efficiency



Isotropic luminosity: $L^{\rm iso} = 4\pi r^2 \times$ Energy flux



Isotropic luminosity (color) and direction of flux.

□Magnetic component

- $L/\dot{M}_{\rm in}$ increases with increasing $|a^*|$.
- It becomes dominant in the ratio of total energy, $a^* < -0.5, a^* \geq 0.5$.
  →**The BZ mechanism** (energy from BH spin).

□Kinetic component

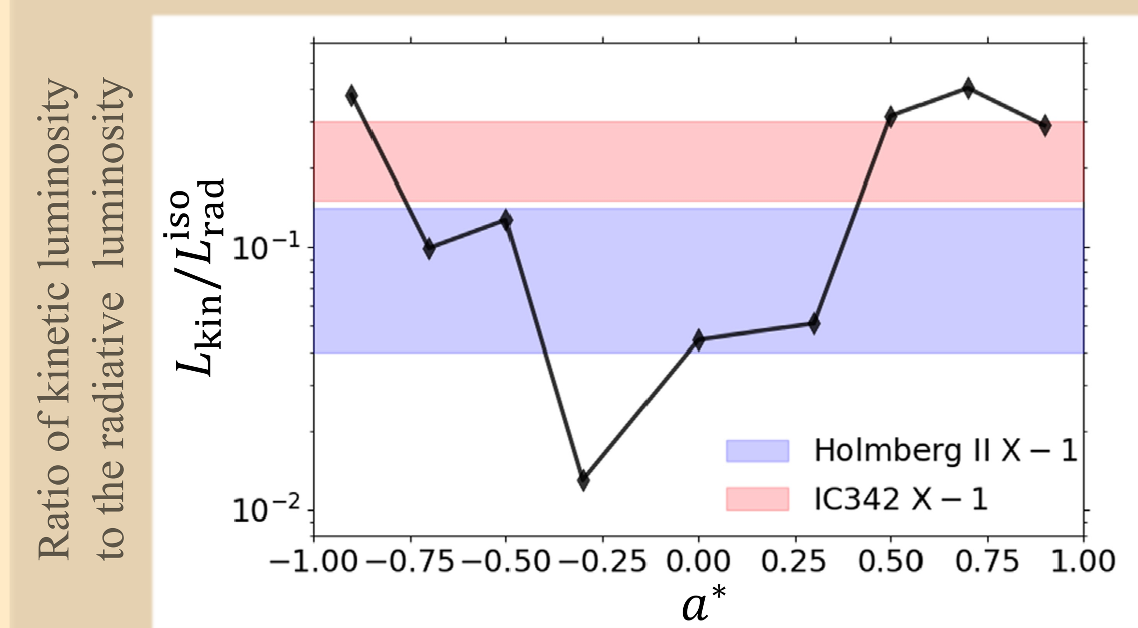
- $L/\dot{M}_{\rm in}$ slightly increases with increasing $|a^*|$.
- Never the most dominant.

□Radiative component

- $L/\dot{M}_{\rm in}$ slightly increases with increasing a^*.
- The radiative component occupies over 50% of total luminosity for $-0.5 \leq a^* < 0.5$.
  → **Energy supply from the disk (Without BZ)**

Astrophysical Implication

■Comparison with observations of the ULXs



The present simulation results suggest,

IC342 X-1 High spin model ($a^* = -0.9, a^* \geq 0.5$)
Holmberg II X-1 Low spin model ($-0.7 \leq a^* \leq 0.3$)

→ Increasing $|a^*|$.
→ Extraction of BH spin energy via magnetic field becomes more pronounced.
→ Increasing jet power.
&
The radiative luminosity dominates in low spin models.

Conclusion

We performed a two-dimensional axisymmetric GR-RMHD simulation of supercritical accretion onto Kerr BHs, and investigated the BH spin dependence of the mass accretion, the mass outflow, and Luminosity.

- **Results**
  - **Even in supercritical accretion disks with much radiation, energy released by the BZ mechanism (magnetic field) is dominant in $a^* < -0.5, a^* \geq 0.5$.**
  - **Radiative component occupies over 50% of total luminosity for $-0.5 \leq a^* < 0.5$.**
- **Discussion**
  - **The present simulation results suggest BH spin parameter for the ULXs, IC342 X-1 High spin model ($a^* = -0.9, a^* \geq 0.5$), Holmberg II X-1 Low spin model ($-0.7 \leq a^* \leq 0.3$).**