Simulating Accretion Disks and Jets Around Prograde and Retrograde Black Holes

Author: Kan Cheuk Kwan; Supervisor: Prof. Jane Lixin Dai; Co-Supervisor: Tom Kwan
Major in Physics (Intensive)

Name: Kan Cheuk Kwan
University No.: 3035785415
Student's Major: Physcis (Intensive)
Poster No.: B11
Research Colloquium for Science UG Students 2023-24

Abstract

Black holes (BHs) attract surrounding materials and gain energy by consuming them continuously. On the other hand, BHs emit energy by launching relativistic jets. In this research, we aim to explore factors that affects the jet strength, and compare the jet strength of prograde and retrograde BHs. GRRMHD simulations are carried out to simulate the behaviors of accretion flows and jets in BH super-Eddington accretion system with different BH spins. It is found that jet strength is affected by the (1) **BH spin**, (2) **magnetic flux through the event horizon**, and (3) **BH accretion rate (a new result not found in previous research)**. Moreover, **prograde** BHs are found to launch **stronger jets** than retrograde BHs **(another new result)**, probably due to difference in **rotational speed of magnetic field lines** in jets and accretion disks.

Introduction

1. Black Hole (BH)

- Extremely dense celestial body predicted by Einstein's theory of general relativity
- Very strong gravity (even light cannot escape)
- Astrophysical BHs have two fundamental parameters: **mass** and **spin** (spin parameter $a \in [-1, 1]$ indicating BH rotation speed and direction)

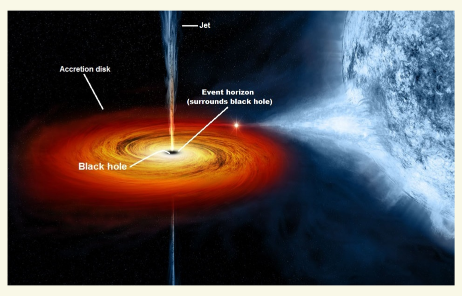

Figure 1: An illustration of a BH with accretion disk and jet

2. Accretion Disk
   - BHs grow (gaining mass and energy) by consuming materials like gas
   - Gas forms an **accretion disk** around the BH before falling in
   - **Prograde** ($a > 0$): BH and the accretion disk rotate in the same direction
   - **Retrograde** ($a < 0$): BH and the accretion disk rotate in the opposite directions (not well studied)

3. Relativistic Jet (Note: Yes, energy can be extracted out of BHs!)

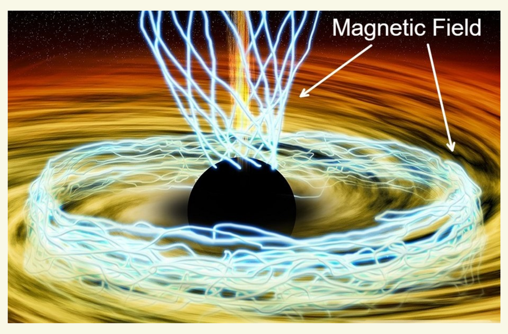

Figure 2: Magnetic field around BH

- highly collimated and energetic materials and radiation ejected from BHs
- speeds faster than 10% of the speed of light
- produced by the Blandford-Znajek (BZ) mechanism
  - A purely **general relativistic effect** in which BH rotational energy is extracted with the help of magnetic field
  - Stronger jet if BH rotates faster or magnetic field is stronger

4. Different Modes of BH Accretion
   - Three possible modes depending on how fast BH accretes matter
   - **Super-Eddington accretion**: BH consumes gas too quickly and standard accretion theory breaks

	Hot Accretion	Thin Disk	**Super-Eddington**
Mass accretion	Slow	Intermediate	Very Quick
Previous research	Better studied	Better studied	Less studied

Research Questions

We carry out numerical simulations to study the production of jets in BH super-Eddington accretion. In particular, we aim to answer these 2 questions:

1. **What sets the power of jets in BH super-Eddington accretion?**
2. **Does the BH spin direction affect the jet power in this scenario?**
   (Spoiler alert: Previous research studies say "no" but see our results!)

Motivation: The answers to these questions are important for understanding the growth of black holes and galaxies in the early universe. Also both super-Eddington accretion and retrograde BHs are challenging and under-explored topics.

Method: GRRMHD Simulation

General Relativistic Radiative Magnetohydrodynamic

State-of-the-art code combining the theories of (1) radiation, (2) general relativity, (3) electromagnetism, and (4) fluid dynamics

Code - Governing equations

(1) Mass conservation: total mass of the whole system remains the same

$$\nabla_\mu(\rho_0 u^\mu) = 0 \qquad (1)$$

(2) Magnetic flux conservation: total amount of magnetic flux remains the same

$$\nabla_\nu(*F^{\mu\nu}) = 0 \qquad (2)$$

(3) Energy-momentum conservation: total amount of energy and momentum remains the same

$$\nabla_\mu(T^\mu_\nu + R^\mu_\nu) = 0 \qquad (3)$$

where ρ_0 is rest mass density, u^μ is contravariant 4-velocity, $*F^{\mu\nu}$ is dual of EM tensor, T^μ_ν is stress-energy tensor, and R^μ_ν is radiation stress-energy tensor.

Analysis - Physical parameters

(1) **BH accretion rate** $\dot{M}$
- amount of gas rest mass going through the BH event horizon in unit time
- indicate the **speed of accretion**

(2) **Dimensionless magnetic flux** $\phi_{\rm BH}$
- number of magnetic field lines through the event horizon in unit time
- indicate the **strength of magnetic flux** (a key quantity for jet launching)

(3) **Jet efficiency** $\eta_{\rm jet}$
- jet power (energy output) divided by accretion power ($\dot{M}c^2$) (energy input)
- fraction of energy input being converted into output through jet
- indicate the **strength of jets**

Results and Discussion

What determines the jet strength?
Spin a, Magnetic flux $\phi_{\rm BH}$, and BH accretion rate $\dot{M}$

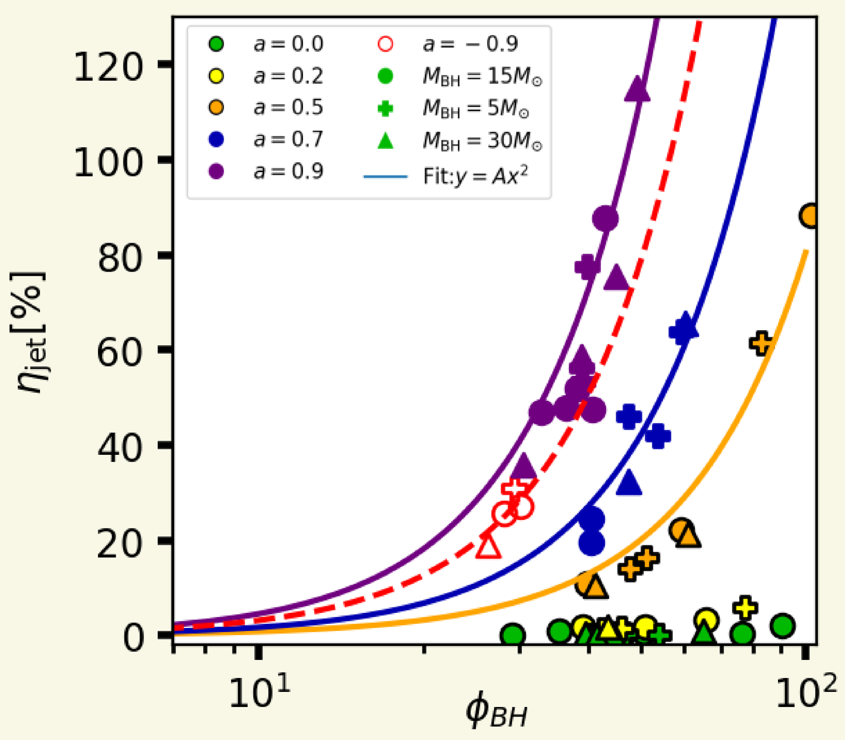

Figure 3: $\eta_{\rm jet}$ vs $\phi_{\rm BH}$

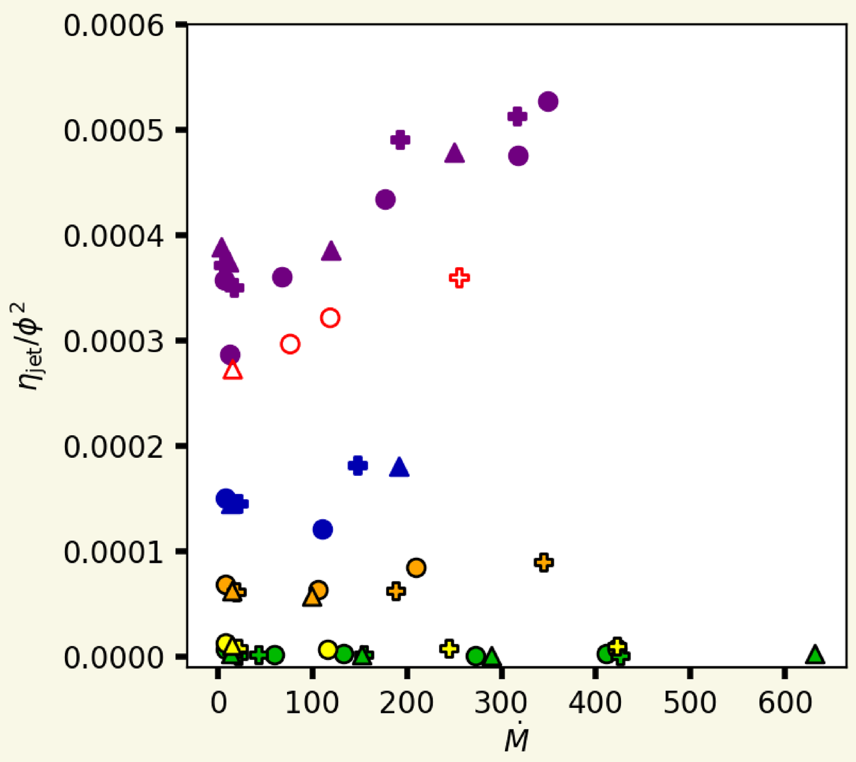

Figure 4: $\eta_{\rm jet}/\phi^2_{\rm BH}$ vs a

- **Magnetic flux**: Jet efficiency $\eta_{\rm jet}$ is *approximately* proportional to square of magnetic flux $\phi_{\rm BH}$ for fixed BH spin a.

$$\eta_{\rm jet} \propto \phi^2_{\rm BH}$$

- **BH accretion rate**: Jet efficiency $\eta_{\rm jet}$ is *not exactly* proportional to $\phi^2_{\rm BH}$ for fixed BH spin a. **A higher BH accretion rate increases the jet efficiency (new result).**

- **BH spin**: higher spin $a \longrightarrow$ higher jet efficiency (for prograde BHs)
- **Sometimes the jet efficiency exceeds 100%! This means energy is extracted out of the BH.**

Check the animations here!

Prograde   Retrograde

BH spin direction affects the jet efficiency $\eta_{\rm jet}$? Yes!

Previous research: According to Narayan et al (2022) and Ricarte et al (2023),

$$\frac{\eta_{\rm jet}}{\phi^2_{\rm BH}} = \frac{\kappa}{4\pi}\Omega^2_{\rm H}[1 + 1.38\Omega^2_{\rm H} - 9.2\Omega^4_{\rm H}] \qquad (4)$$

where $\Omega_H = a/(1 + \sqrt{1 - a^2})$. Due to the even indices in equation 4, the value of $\eta_{\rm jet}/\phi^2_{\rm BH}$ should not be affected by the sign of BH spin a, i.e. red points and lines should overlap with purple ones in Figure 3 and 4.

My results: Asymmetry in prograde and retrograde BHs

Prograde BHs (purple line and symbols) have higher jet efficiency $\eta_{\rm jet}$ than retrograde BHs (dotted line and hollow symbols) when the vales of magnetic flux $\phi_{\rm BH}$ and mass accretion rate $\dot{M}$ are the same, which is strikingly different from previous research studies.

Possible reason: **Slower rotation of magnetic field lines in jets** of retrograde BHs

- Magnetic field lines in jets carry energy along the jet $\longrightarrow$ their rotational speed may be related to the jet efficiency
- It is found that field lines in jets of retrograde BHs have lower rotational speed than those of prograde BHs
  - possibly because rotation of magnetic field lines in accretion disks is also slower for retrograde BHs

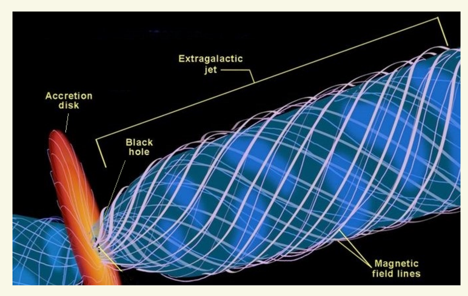

Figure 5: Rotation of magnetic field lines in jets

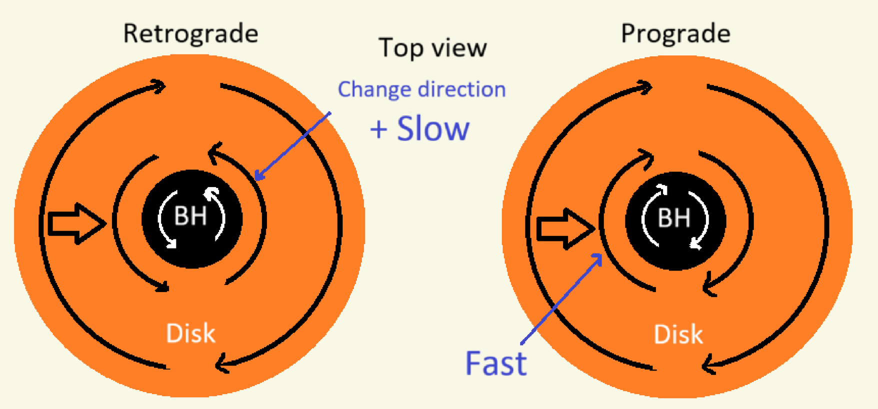

Figure 6: Rotation of magnetic field lines in accretion disks of prograde and retrograde BHs

** I am writing a research paper (**Kan et al. in prep**) based on the results obtained through this FYP
** I plan to carry more analysis to understand the asymmetry in η_{jet} of prograde and retrograde BHs

References

McKinney, J. C., Tchekhovskoy, A., Sadowski, A., Narayan, R. (2014, May 30). Three-dimensional general relativistic radiation magnetohydrodynamical simulation of super-Eddington accretion, using a new code harmrad with M1 closure. Monthly Notices of the Royal Astronomical Society, 441(4), 3177–3208. https://doi.org/10.1093/mnras/stu762
Narayan, R., Chael, A., Chatterjee, K., Ricarte, A., Curd, B. (2022, February 8). Jets in magnetically arrested hot accretion flows: geometry, power, and black hole spin-down. Monthly Notices of the Royal Astronomical Society, 511(3), 3795–3813. https://doi.org/10.1093/mnras/stac285
Ricarte, A., Narayan, R., Curd, B. (2023, August 31). Recipes for Jet Feedback and Spin Evolution of Black Holes with Strongly Magnetized Super-Eddington Accretion Disks. The Astrophysical Journal Letters, 954(1), L22. https://doi.org/10.3847/2041-8213/aceda5
Tchekhovskoy, A. (2014, October 8). Launching of Active Galactic Nuclei Jets. The Formation and Disruption of Black Hole Jets, 45–82. https://doi.org/10.1007/978-3-319-10356-3_3