

# Black Hole Accretion Disk Simulations

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**Abstract.** Understanding the impact of magnetic field topology on the evolution of black hole accretion disks is essential for interpreting high-energy astrophysical phenomena such as jet formation and relativistic outflows. This work presents a comparative study of two different magnetic configurations—dipolar and multipolar—in the context of Magnetically Arrested Disks (MADs), using two-dimensional general relativistic magnetohydrodynamic (GRMHD) simulations carried out with the *iharm3d* code. Both setups are based on a modified Fishbone-Moncrief torus in Kerr spacetime. We analyze the time evolution of mass accretion rate, magnetic flux, angular momentum flux, and energy extraction efficiency. The results show that dipolar configurations lead to a more stable and efficient MAD state, whereas multipolar topologies generate irregular accretion patterns and lower energy extraction.

**Resumo.** A compreensão do impacto da topologia do campo magnético na evolução dos discos de acreção de buracos negros é essencial para interpretar fenômenos astrofísicos de alta energia. Este trabalho apresenta um estudo comparativo de duas configurações magnéticas diferentes — dipolar e multipolar — no contexto de Discos Magneticamente Detidos (MADs), utilizando simulações de magnetohidrodinâmica relativística geral (GRMHD) em 2D realizadas com o código *iharm3d*. Ambas as configurações baseiam-se em um toro de Fishbone-Moncrief modificado no espaço-tempo de Kerr. Analisamos a evolução temporal da taxa de acreção de massa, fluxo magnético, fluxo de momento angular e eficiência de extração de energia. Os resultados mostram que as configurações dipolares levam a um estado MAD mais estável e eficiente, enquanto as topologias multipolares geram padrões de acreção irregulares e menor extração de energia.

**Keywords.** Black hole physics – Plasmas – Gravitation

## 1. Introduction

The study of black hole accretion disks, particularly in regimes dominated by strong magnetic fields, is fundamental to understanding relativistic jet formation and black hole feedback. General relativistic magnetohydrodynamics (GRMHD) simulations allow for the investigation of the nonlinear interplay between fluid dynamics, magnetic fields, and spacetime curvature.

One widely used model is the Fishbone-Moncrief torus (Fishbone & Moncrief 1976), which allows for the development of the magnetorotational instability (MRI) (Balbus & Hawley 1991) and the transition to the Magnetically Arrested Disk (MAD) state (Tchekhovskoy et al. 2011). In the MAD regime, the accretion flow is strongly influenced by accumulated magnetic flux near the event horizon.

This report investigates the dynamical differences between single (dipolar) and double (multipolar) magnetic loop structures embedded within a torus using the *iharm3d* code.

## 2. GRMHD Formulation and Setup

We utilize the *iharm3d* code (Gammie et al. 2003; Porth et al. 2017) to solve the GRMHD equations in the Kerr metric. The conservation laws for mass and energy-momentum are  $\nabla_{\mu}(\rho u^{\mu}) = 0$  and  $\nabla_{\mu}T^{\mu\nu} = 0$ , where the stress-energy tensor includes both fluid and electromagnetic components (Komissarov 1999).

### 2.1. Torus Setup and Magnetic Topology

The simulations use a modified Fishbone-Moncrief torus. To model the MAD regime, we utilize the vector potential  $A_{\phi}$ . For

the single loop (dipolar) case, we use the "RYAN" configuration:

$$A_{\phi} = \sin^3(\theta) \left( \frac{r}{r_{in}} \right)^3 e^{-r/400} \frac{\rho_{av}}{\rho_{max}} - 0.2 \quad (1)$$

For the double loop (multipolar) case, the potential is modified to:

$$A_{\phi} = \cos^4(\theta) \sin^3(\theta) \left( \frac{r}{r_{in}} \right)^3 e^{-r/400} \frac{\rho_{av}}{\rho_{max}} - 0.2 \quad (2)$$

The grid resolution was set to  $128 \times 32 \times 1$  due to computational constraints.

## 3. Results and Discussion

### 3.1. Single Magnetic Field Loop

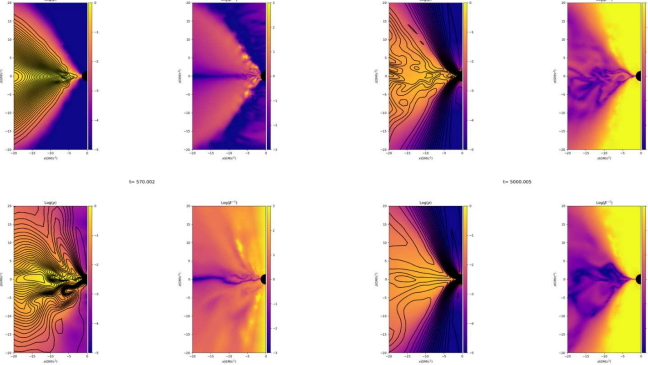
In the dipolar configuration, the simulation reveals the evolution of logarithmic density and plasma beta (Fig. 1).

The mass accretion rate  $\dot{M}$  presents an initial transient phase followed by a relatively stable plateau (Fig. 2). This suggests the system reaches a quasi-stationary MAD regime. The magnetic flux  $\Phi$  also saturates, consistent with the accumulation of field lines at the inner disk edge. The energy extraction efficiency saturates around a well-defined value, consistent with the Blandford-Znajek mechanism.

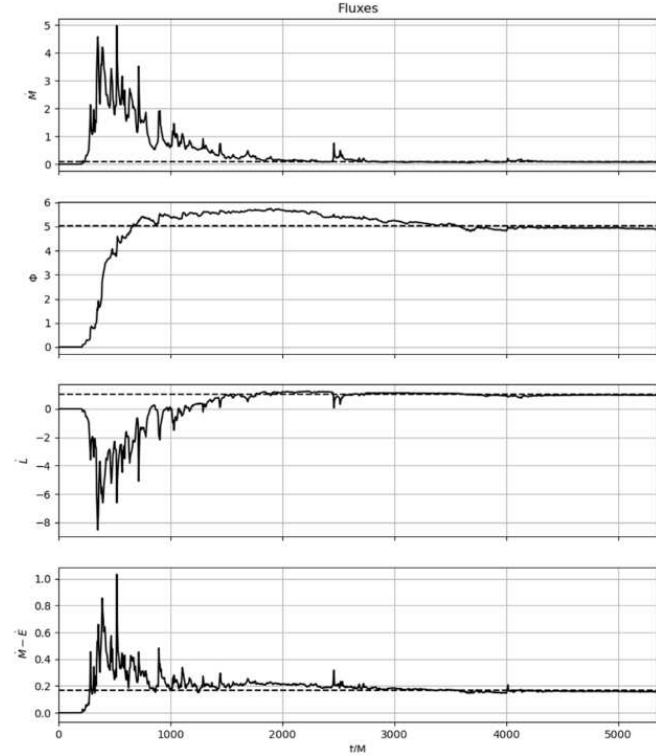
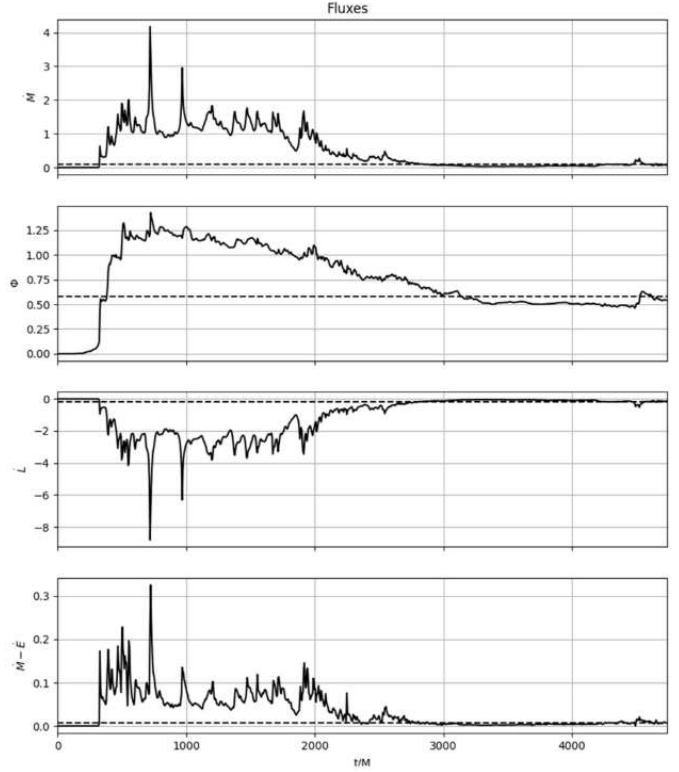
### 3.2. Double Magnetic Field Loop

The multipolar topology (Fig. 3) exhibits a more chaotic evolution compared to the single loop case.

$\dot{M}$  is characterized by high-frequency fluctuations and intermittent spikes (Fig. 4), suggesting reconnection events. The



**FIGURE 1.** Distributions of logarithmic density  $\log(\rho)$  and plasma beta  $\log(\beta^{-1})$  for dipole poloidal magnetic field loops. Evolution shown from early to late times.



**FIGURE 2.** Time evolution of physical fluxes for the single loop simulation: mass accretion  $\dot{M}$ , magnetic flux  $\Phi$ , angular momentum  $\dot{L}$ , and energy extraction efficiency  $(\dot{M} - \dot{E})$ .

**FIGURE 4.** Time evolution of physical fluxes for the multipolar loop simulation. Note the irregular accretion patterns compared to Fig. 2.

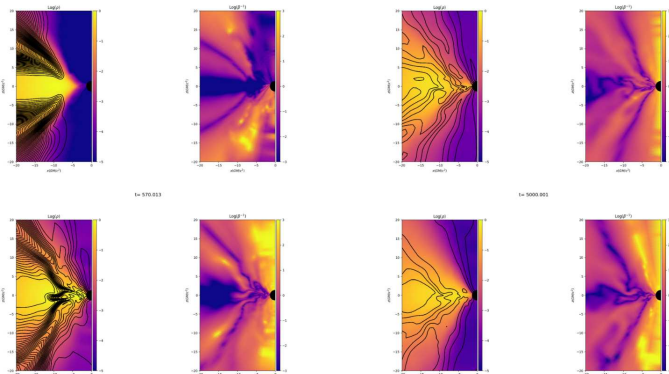
magnetic flux does not reach the same saturation level as the dipolar case, showing multiple peaks and valleys. This points to a non-stationary state with variable magnetic arrest and lower energy extraction efficiency.

#### 4. Conclusions

We demonstrated that magnetic field topology critically influences the evolution of black hole accretion flows. Dipolar configurations promote a stable, efficient MAD state with high magnetic flux saturation. In contrast, multipolar configurations lead to irregular dynamics and reduced efficiency in energy extraction.

#### References

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**FIGURE 3.** Distributions of logarithmic density  $\log(\rho)$  and plasma beta for the double magnetic loop configuration.