The Effects of Gas Angular Momentum on Forming Magnetically Arrested Disks and Launching Powerful Jets

Tom M. Kwan 1, Lixin Dai 1, and Alexander Tchekhovskoy 2, 3

1 Department of Physics, The University of Hong Kong, Pokfulam Road, Hong Kong
2 Department of Physics & Astronomy, Northwestern University, Evanston, IL 60208, USA
3 Center for Interdisciplinary Exploration & Research in Astrophysics (CIERA), Evanston, IL 60208, USA

ABSTRACT

In this Letter, we investigate jet-launching abilities of Bondi-like accretion flows with zero or low specific angular momentum by performing 3D general relativistic magnetohydrodynamic simulations. In order to check if relativistic jets can be launched magnetically, we thread the accretion flow with large-scale poloidal magnetic field, and choose a rapidly spinning black hole. We demonstrate that the magnitude of the initial gas specific angular momentum primarily controls whether the disk can reach and sustain the magnetically arrested disk (MAD) state that launches very powerful jets, at $\gtrsim 100\%$ energy efficiency. We find that MAD forms in the presence of even a very small amount of specific angular momentum, and episodic jets with an average energy efficiency of $\sim 10\%$ can still form even when the gas has zero initial angular momentum. Our results give plausible explanations to why jets can be produced from various astrophysical systems that lack large gas specific angular momenta, such as Sgr A*, wind-fed X-ray binaries, tidal disruption events, and long-duration gamma-ray bursts.

Keywords: Accretion (14) — Black holes (162) — Galactic center (565) — Gamma-ray bursts (629) — Massive stars (732) — High mass x-ray binary stars (733) — Jets (870) — MHD (1964)

1. INTRODUCTION

Gas accretion onto black holes (BHs) is common in many astrophysical systems. The accreting gas is usually assumed to carry some angular momentum and form a disk. Magnetorotational instability (MRI) transports the angular momentum outwards (Balbus & Hawley 1998), allowing gas to accrete. In this process, the gas mass-energy is converted to energy power relativistic jets, winds and radiation, as observed from active galactic nuclei (AGNs), BH X-ray binaries (XRBs), tidal disruption events (TDEs), etc. Some of the popular accretion disk models include the advection-dominated accretion flow (ADAF, e.g., Narayan & Yi 1994, 1995; Yuan & Narayan 2014), standard $\alpha$-disk (Shakura & Sunyaev 1973; Novikov & Thorne 1973) and slim disk (Abramowicz et al. 1988) models, which apply to disks at different accretion rates.

While all disk models described above assume the disk has a relatively large specific angular momentum, some astrophysical systems can carry very low gas angular momentum, such as Sgr A* (Melia 1992; Narayan et al. 1995; Ressler et al. 2018), long gamma-ray bursts (GRBs, Fryer 1999), tidal disruption events (TDEs, Rees 1988) and wind-fed high-mass X-ray binaries (HMXBs, Smith et al. 2002; Tauris & van den Heuvel 2006). Accretion flows with low gas angular momentum are less studied. Yet it is important to understand whether such accretion flows can produce powerful emissions, winds, and jets.

The simplest model for accretion flows with zero angular momentum is the Bondi accretion model (Bondi 1952), in which gas accretes steadily in a spherically symmetric fashion. Bondi-like accretion flows with low angular momentum have been extensively studied with hydrodynamic simulations, which examine the behavior of the accretion flow on large scales (Suková & Janiuk 2015; Suková et al. 2017), and show that a thick equatorial torus structure can form...
near the equator as the flow hits the centrifugal barrier. As a result, part of the inflow can form an outflow, which can lead to energy feedback on the surroundings (e.g. Proga & Begelman 2003; Janiuk et al. 2008; Lee & Ramirez-Ruiz 2006; Murgia-Berthier et al. 2020). However, these studies have neglected the magnetic or general relativistic effects, which play an essential role in determining the behavior of inner accretion flows and in particular the prospect of launching relativistic jets (Blandford & Znajek 1977).

The dynamical evolution of magnetized plasma around black holes and the production of jets involves nonlinear processes and generally lacks obvious symmetries. This makes general relativistic magnetohydrodynamic (GRMHD) simulations particularly attractive for modeling these systems (e.g., Gammie et al. 2003; De Villiers & Hawley 2003; Tchekhovskoy et al. 2011; McKinney et al. 2012; White et al. 2016; Porth et al. 2017; The Event Horizon Telescope Collaboration et. al. 2019). These GRMHD simulations usually start from gas in the configuration of a torus or disk with its motion-dominated rotation (see reviews by Tchekhovskoy et al. 2012; Davis & Tchekhovskoy 2020). They show that if large-scale ordered magnetic fields are supplied to such disks, the accretion flow would drag sufficient magnetic fluxes to the vicinity of the black hole, and magnetically arrested disks (MADs, Narayan et al. 2003, see also Bisnovatyi-Kogan & Ruzmaikin 1974, 1976) will form. In MADs, magnetic field significantly impacts the inner disk dynamics, and very powerful jets can be produced if the black hole spins rapidly (Blandford & Znajek 1977): In fact, jet power can even exceed the accretion power, resulting in net energy extraction from the black hole (Tchekhovskoy et al. 2011).

In contrast, the behavior of low angular momentum accretion flows is much less clear and has not been extensively explored with GRMHD simulations. In particular, the role of gas angular momentum for launching powerful jets remains poorly understood. Komissarov & Barkov (2009) studied the spherical accretion of magnetized gas with two-dimensional GRMHD simulations and showed that such accretion flow can become highly magnetized near the event horizon and launch outflows. More recently, several studies employed 3D GRMHD simulations to investigate Bondi-like accretion flow and the resulting feedback processes. Ressler et al. (2021) studied spherical accretion flow threaded with large-scale magnetic field at different inclinations with respect to the spin axis of the BH and explored how the jet strength depends on the inclination. Kaaz et al. (2022) studied Bondi-Hoyle-Lyttleton (BHL) accretion onto a spinning BH traversing through a magnetized gaseous medium and showed such accretion could power relativistic jets. However, how the jet power depends on the gas angular momentum has not been systematically studied.

In this work, we focus on investigating the link between the magnitude of the gas specific angular momentum and the power of the relativistic jets. We carry out three fully 3D GRMHD simulations of magnetized Bondi-like accretion flows with initially no or very low angular momentum around rapidly spinning black holes. We study the properties of the quasi-steady state accretion flow, and investigate how the magnetic flux and gas coexist near the black hole. We demonstrate that both non-rotating and slowly rotating accretion flows can produce relativistic jets. However, the initial angular momentum of the gas needs to reach a small critical value to robustly sustain the MAD state and its powerful jets. We introduce our methodology and simulation setup in Section 2. We present the results in Section 3, and discuss and summarize them in Section 4.

2. METHODOLOGY

2.1. Governing equations

We carry out 3D time-dependent GRMHD simulations using the HARM code (Gammie et al. 2003; McKinney & Gammie 2004; Tchekhovskoy et al. 2011; McKinney et al. 2012). The code solves the following conservation equations:

\[ \nabla_\mu (\rho u^\mu) = 0 \]

\[ \nabla_\mu T^{\mu}_\nu = 0 \]  

where \( \rho \) is the rest-mass density of the gas in the fluid frame, \( u^\mu \) is the gas 4-velocity, \( T^{\mu}_\nu \) is the energy stress tensor, which includes matter (MA) and electromagnetic (EM) terms,

\[ T^{\mu}_\nu = T^{EM\mu}_\nu + T^{MA\mu}_\nu \]

\[ T^{MA\mu}_\nu = (\rho_0 + u_g + p_g) \ u^\mu u_\nu + p_g \delta^{\mu}_\nu \]

\[ T^{EM\mu}_\nu = \beta^2 u^\mu u_\nu + p_b \delta^{\mu}_\nu - b^\mu b_\nu \]  

where \( u_g \) is the gas internal energy density with the adiabatic index of \( \gamma = 4/3 \), \( p_g = (\gamma - 1) u_g \) is the gas pressure, \( p_b = b^\mu b_\nu / 2 = b^2 / 2 \) is the magnetic pressure, \( b^\mu \) and \( b_\nu \) are the contravariant and covariant fluid-frame magnetic field...
Effect of Gas Angular Momentum on the Jet Launching

3

u

angular momentum is characterized by the circularization radius $R_c$, at which the centrifugal force is large enough to counterbalance the inward gravitational force. The three simulations have maximum specific angular momentum corresponding to $R_c = 0$ (model a09rc0), 10$r_g$ (model a09rc10), and 50$r_g$ (model a09rc50), respectively. The specific angular momentum of a Keplerian, equatorial circular orbit is:

$$l_K(r) = \frac{\sqrt{7}(r^2 - 2a\sqrt{r} + a^2)}{r\sqrt{r^2 - 3r + 2a\sqrt{r}}}.$$  

Hence we set the gas initial maximum specific angular momentum to be:

$$l_{\text{max}} = \begin{cases} 
0 & \text{for } R_c = 0 \\
l_K(r = R_c) & \text{for } R_c = 10r_g \text{ or } 50r_g
\end{cases}.$$  

More details of the initial specific angular momentum distribution across the gas flow are given in Appendix A.

We thread the accretion flow with a relatively weak poloidal magnetic field. The magnetic flux is described by the magnetic flux function $\Psi(r, \theta) = r(1 - |\cos\theta|)$, which describes parabolic magnetic flux distribution (Tchekhovskoy et al. 2008). This description ensures that the plasma beta $\beta \equiv p_g/p_b$ is asymptotically constant everywhere. $\beta$ is set to have a minimum value of 100 along the equator, so that the initial magnetic field in the disk is subdominant.
2.3. Diagnostics

We categorize the gas flow into three different regions: 1) the jet region, where $\sigma = b^2/\rho > 1$; 2) the wind region, where the conditions $u' > 0$ and $\sigma < 1$ are both satisfied; 3) the disk region, where the conditions $u' < 0$ and $\sigma < 1$ are both satisfied. (We note that a small inflow region very close the black hole can have $\sigma > 1$, but excluding this region from the disk only makes minor changes to our results.) The above conditions define the boundaries between these regions, i.e., the jet-wind boundary has $\sigma = 1$ and the disk-wind boundary has $u' = 0$. Below we provide a summary of the definitions used for computing the various quantities.

The rest-mass accretion rate flowing inwards through a sphere of radius $r$ is

$$\dot{M} = -\int \rho u_r dA_{\theta \phi},$$

where $dA_{\theta \phi} = \sqrt{-g} d\theta d\phi$. This gives us the accretion rate onto the black hole $\dot{M}_H$ when evaluated at the event horizon $r_H$.

The absolute magnetic flux through the black hole event horizon is

$$\Phi_H = \frac{1}{2} \int |B'| dA_{\theta \phi}$$

which is integrated over the event horizon. One can define a dimensionless magnetization parameter, the “MADness parameter”, by normalizing $\Phi_{BH}$ with $\dot{M}_H$ (Tchekhovskoy et al. 2011)

$$\phi_H = \frac{\Phi_H}{\sqrt{\dot{M}_H r_g^2 c}}.$$}

The disk enters the MAD state when $\phi_H \gtrsim 40$. In practice, when we compute dimensionless quantities like $\phi$ and various efficiencies by normalizing some quantity $Q(t)$ with $\dot{M}_H(t)$, we smooth $\dot{M}_H(t)$ with a Gaussian function over a moving window centered at time $t$ and with a standard deviation of 1000 $r_g/c$ in order to reduce fast fluctuations.

The energy flux flowing out through a sphere of radius $r$ is

$$\dot{E} = -\int T_{t} dA_{\theta \phi}.$$}

Using this, we can calculate the net outflow efficiency as

$$\eta(r) \equiv \frac{\dot{E}(r) + \dot{M}(r)}{\dot{M}_H}.$$}

The accretion efficiency $\eta_H$ is defined as $\eta(r)$ evaluated at the event horizon. When $\eta_H > 100\%$, the accretion process results in a net energy extraction out of the BH, typically caused by the energy extraction rate in electromagnetic form through the BZ process around a fastly spinning BH exceeding the disk energy supply rate in the form of rest-mass energy. In addition, we can evaluate the jet energy flux and the jet energy efficiency as:

$$\dot{E}_{\text{jet}} = -\int T_t (\sigma > 1) dA_{\theta \phi},$$

$$\eta_{\text{jet}} \equiv \frac{\dot{E}_{\text{jet}}(r)}{\dot{M}_H}.$$}

In order to obtain the radial profile of a quantity $Q(r)$, we average it over spherical shells and weigh it by the gas density $\rho$:

$$\langle Q(r) \rangle_\rho \equiv \frac{\int dA_{\theta \phi} \rho Q}{\int dA_{\theta \phi} \rho}.$$}

We can define the geometric half-angular thickness, $(H/R)$, of the flow as:

$$\frac{H}{R} \equiv \left( \frac{\int \rho(\theta - \theta_{\text{mid}})^2 dA_{\theta \phi}}{\int \rho dA_{\theta \phi}} \right)^{1/2},$$

where $\theta_{\text{mid}} \equiv \langle \theta \rangle_\rho$ is the polar angle of the disk mid-plane.
3. RESULTS

3.1. Time evolution of the accretion flow

We run all three simulations out to at least $t = 50000\,r_g/c$. The flows reach an inflow equilibrium out to $r \gtrsim 200\,r_g$ in all runs. We show the evolution of the accretion flows in the three runs with different $R_c$ in Fig. 1. Initially, the outer gas falls in radially without sufficient support from angular momentum. At the same time, a centrifugally supported structure starts to form close to the black hole, owing to two factors. 1) The small initial gas specific angular momentum (as in our model a09rc10 and a09rc50) can result in the formation of a centrifugal barrier, which has been demonstrated in previous analytical calculations and hydrodynamical simulations of Bondi-like accretion (e.g., Proga & Begelman 2003; Lee & Ramirez-Ruiz 2006; Suková et al. 2017). 2) Due to the GR frame-dragging effect, the gas near black hole can gain some angular momentum. Therefore, even in our a09rc0 model, the spherical symmetry is still broken due to the fast spin of the black hole and the vertical configuration of the magnetic flux near the black hole. In all simulations, geometrically thick disk structures (shaded with a light blue color) form close to the black holes. In addition, wide-angle winds and relativistic jets are launched.

Figure 1. We show snapshots of a vertical slice from the inner regions of the 3D GRMHD simulations with a09rc0 ($R_c = 0$, top), a09rc10 ($R_c = 10r_g$, middle), or a09rc50 ($R_c = 50r_g$, bottom), at different times $t = (0, 3000, 35000, 48000)\,r_g/c$ (left to right). The color shows gas the rest mass density $\rho_0$. The black lines indicate the magnetic field lines, for which the thickness represents the magnetic field strength. The pink contours show the boundary of the jet with $\sigma = 1$. The blue contours show the disk-wind (i.e., inflow-outflow) boundary, which has $u^r = 0$. In all simulations, geometrically thick disk structures (shaded with a light blue color) form close to the black holes. In addition, wide-angle winds and relativistic jets are launched.
hole. After the formation of the centrifugal barrier, the infalling gas hits on it and develops a shock, which propagates outwards. A high-density bubble expands with the shock (e.g., the regions confined by two blue $u^r = 0$ contours in the snapshots at $t = 3000r_\text{g}/c$). By $t \gtrsim 10000r_\text{g}/c$, the accretion flows have become stable in three simulations, and winds and relativistic jets are launched in all three simulations. The jets drive blast waves into the ambient medium, vacant the gas and prevent accretion onto the black hole along the polar region.

Fig. 2 shows the evolution of the mass accretion rate onto the black hole $\dot{M}_H$ (Eqn. 12), the MADness parameter $\phi_H$ (Eqn. 14), the outflow energy efficiency $\eta_H$ (Eqn. 16) and the jet efficiency $\eta_{\text{jet}}$ (Eqn. 18) as functions of time.$^1$

The rate that gas falls into the black hole initially starts out high. Dragged by the infalling gas, magnetic flux builds up near the black hole, so $\phi_H$ quickly grows and MRI is triggered in the accretion disk. It is apparent that the model a09rc0 has $\phi_H$ growing the fastest, since the gas in this model falls in faster with the lowest initial gas angular momentum. After the disk forms, $\dot{M}_H$ drops with time, until a later phase at $t \sim 20000r_\text{g}/c$ when the accretion becomes quasi-steady.

Interestingly, though magnetic fluxes accumulate faster in model a09rc0 and a09rc10 in the initial phase, after $t \sim 20000r_\text{g}/c$, $\phi_H$ in these two models decrease and eventually to below the MAD threshold. In contrast, we see $\phi_H$ grows the slowest in model a09rc50 which has the largest initial specific angular momentum. However, it can reach and sustain the MAD state and demonstrate characteristic MAD behavior: high variability in $\Phi_H$ and $\eta_H$ and the production of powerful jets with $\eta_{\text{jet}} > 100\%$ from the Blandford-Znajek process ($\eta_{\text{jet}}$ is plotted using solid line in the bottom panel). We will give more analysis of the behavior of magnetic flux in Section 3.3. In addition, there is a significant correlation between $\eta_H$ and $\eta_{\text{jet}}$, meaning most of the energy produced in the accretion process is carried away by jet.

In the following sections, we compute the average values of a few physical quantities in the window of $t = 20000$–$50000r_\text{g}/c$. In this time window, both gas accretion and $\phi_H$ in these two models decrease and eventually to below the MAD threshold. In contrast, we see $\phi_H$ grows the slowest in model a09rc50 which has the largest initial specific angular momentum.

In practice, here we measure the BH mass $\dot{M}_H$ and energy $\dot{E}_H$ fluxes at $r = 6r_\text{g}$ to avoid the potential contamination of $\dot{M}$ and $\dot{E}$ by the numerical density floors near the horizon, since the true time-averaged $\dot{M}_H$ and $\dot{E}_H$ (if uncontaminated by the density floors) should remain constant near the horizon when the flow has reached a quasi-steady state.

---

$^1$ In practice, here we measure the BH mass $\dot{M}_H$ and energy $\dot{E}_H$ fluxes at $r = 6r_\text{g}$ to avoid the potential contamination of $\dot{M}$ and $\dot{E}$ by the numerical density floors near the horizon, since the true time-averaged $\dot{M}_H$ and $\dot{E}_H$ (if uncontaminated by the density floors) should remain constant near the horizon when the flow has reached a quasi-steady state.
3.2. The radial and angular structure of the flow

In this section we investigate the radial and inclination profiles of accretion flow in the window of $t = 20000–50000 \, r_g/c$ when the inner accretion flow becomes quasi-steady. Fig 3 shows the radial profiles of: (a) the gas density, $\rho$, (b) the ratio of the lab-frame radial velocity, $v^r = u^r/u^t$, to the free-fall velocity $v_{ff}$ (in practice $v^r/v_{ff} = -u^r/u_{rr}^t$ with $u_{rr}^t$ given by Eqn. 9) , (c) the ratio of the lab-frame angular velocity, $\Omega = u^\phi/u^t$, to the Keplerian velocity, $\Omega_K = 1/(r_p^{1.5} + a)$, where $r_p = r \sin \theta$ is the cylindrical radius, (d) the geometric half-angular thickness of the inflow, $H/R$, and (e) the Lorentz factor, $\Gamma = \alpha u^t$, where $\alpha = 1/\sqrt{-g^{tt}}$ is the time lapse. All quantities are time-$\theta$-$\phi$-averaged. In addition, quantities in (b)-(c) are further density-weighted to focus on the disk, while $\Gamma$ is further magnetization-weighted to focus on the jet. We plot these quantities out to $1000r_g$, where the shocks have propagated to, so $\rho$, $v^r$ and $\Omega$ of the inflows decline rapidly around that radius.

Figure 3. The time-angle-integrated radial profiles of (a) density $\rho$, (b) lab-frame radial velocity $v^r$ ($\rho$-weighted) over the free-fall velocity $v_{ff}$, (c) lab-frame angular velocity $\Omega$ ($\rho$-weighted) over the relativistic Keplerian angular velocity $\Omega_K$, (d) geometric half-angular disk thickness $H/R$, and (e) Lorentz factor of the jet $\Gamma$ ($\sigma$-weighted). The three different colors denote different models: a09rc0 (red), a09rc010 (yellow) and a09rc50 (blue). The quantities in the inflow and outflow regions in (a)-(c) are plotted using the solid (inflow) and dot-dashed (outflow) lines, respectively. All models produce sub-Keplerian, sub-free-fall, and geometrically thick disks, though the model a09r50 produces the thinnest and fastest rotating disk among the three. The relativistic jets in the models have the peak Lorentz factor $\Gamma = 3 - 4$, at $r \sim 1000r_g$. 

\[ \langle \rho \rangle \propto r^{-1.5} \]

\[ \langle v^r/v_{ff} \rangle_{\rho} \]

\[ \langle \Omega/\Omega_K \rangle_{\rho} \]

\[ H/R \]

\[ \langle \Gamma \rangle_{\sigma} \]

$r \ [r_g]$
One can see that the gas density and radial velocity structures of the accretion flows in the three models are similar in the $r \lesssim 200r_g/c$ inflow equilibrium region. All models produce geometrically thick disks, with model a09rc50 with the largest specific angular momentum producing the least thick disk. The disks completely extend to the event horizon, and their densities still approximately follow the free-fall profile $\rho \propto r^{-1.5}$. The radial inflow velocities are 30-40% of the free-fall velocity in the quasi-steady region. Moreover, despite the different initial conditions, all three accretion inflows acquire some angular momentum and rotate at the frequency of few $\times 0.1\Omega_K$ near the horizon. However, only the model a09rc50 can maintain a near-Keplerian rotation until $r \sim 700r_g$, while the rotation speed in the other two models quickly declines at larger radii. Furthermore, in all models winds are launched close to the black hole and rapidly accelerated. They reach the maximum density within $r = 5r_g$ and terminal velocity within $r = 100r_g$. Lastly, the jets launched in three models have similar acceleration profiles and eventually reach $\Gamma = 3 - 4$. The jet in the model a09rc50 is more steady and slightly faster.

Fig. 4 shows the $\theta$-profiles of (a) $\rho$, (b) $v_r/v_{ff}$ and (c) $\Omega/\Omega_K$, all evaluated on the surface at $r = 100r_g$. These quantities are $t$-$\phi$-$\rho$ averaged. Consistent with the $H/R$ result, the density profile of disk in model a09rc50 is the most concentrated toward the mid plane. Indeed the a09rc50 disk most closely resembles the disks produced in typical GRMHD simulations starting from torus set-ups, though being geometrically thicker. The $v_r$ plot also clearly shows the inflow-outflow boundary moves towards the mid-plane as the gas specific angular momentum increases. The winds reach maximum radial velocities of $v_r \approx 0.1c$ right outside the jet in model a09rc0 and a09rc10, while in a09rc50 model the wind reaches a faster velocity of $v_r \approx 0.2c$. The wind in a09rc50 also has the fastest angular velocity of $\Omega \approx 0.3 - 0.4\Omega_K$, while the winds in model a09rc0 and a09rc10 rotate slower with $\Omega \approx 0.1 - 0.2\Omega_K$. Most interestingly, the behavior of the angular velocity $\Omega$ in model a09rc50 and the other two models are drastically different. Only in model a09rc50 the accretion inflow develops a coherent rotation at all inclinations, while the gas in a09rc0 and a09rc10 still orbit in different directions at different inclinations.

![Figure 4](image-url)
We have shown that an accretion flow needs a minimum specific angular momentum to sustain the MAD state, when it can possibly launch a powerful jet. In the final part of the study, we focus on how the magnetic flux accumulates (or leaks out) in these Bondi-like accretion flows.

We show the snapshots of the gas density and electromagnetic energy flux at $t = 35000r_g/c$ for the a09rc0 and a09rc50 models side to side in Fig. 5. These snapshots demonstrate the characteristic behavior of the magnetic fluxes during the quasi-equlibrium phase. It is apparent that model a09rc0 has a highly non-axisymmetric accretion flow structure. Most strikingly, one can see from panels (b1) and (b2) that even along the mid-plane close to the black hole gas still does not flow inwards along all directions as seen in typical disks, and there is a large azimuthal angle range persistently open for the gas flowing all the way out. The electromagnetic energy fluxes in these out-flowing regions are large, indicating that such regions provide a channel for magnetic flux to leak out from the vicinity of the black hole. We suspect that these “magnetic bubbles” are carried out by the wind or leak out due to buoyancy, which leads to a low level of magnetic flux present near the black hole. Model a09rc10 exhibits a similar behavior as model a09rc0 (not shown). In contrast, model a09rc50 produces a more steady and axisymmetric disk structure. There are still out-flowing regions at high latitudes; however, along the mid-plane the outflows are patchy and not strong enough to disrupt the inflow. It is very probable that some magnetic bubbles still form and flow out for a short range, but later mix with the inflow and get shredded due to gas rotation. The magnetic flux is then brought back by the inflow and supplied to the vicinity of the black hole, which allows the magnetic flux to accumulate and sustain the MAD state. More careful analysis of the interaction of the magnetic flux with gas, which is out of the scope of this paper, will be needed to fully understand the physics here.

### 4. DISCUSSION

#### 4.1. Comparison with previous GRMHD simulations of Bondi-like accretion flows

It is worth mentioning that a few GRMHD simulations of Bondi-like accretion flow have been performed recently, and we compare our results to theirs as below. For example, Ressler et al. (2021) has conducted various simulations of Bondi accretion focusing on understanding how the orientation between the magnetic field and black hole spin axis plays a role in determining the behavior of the accretion flow and the launching of the jet. Their simulation with magnetic field orientation aligned with the black hole spin axis has the configuration resembling our a09rc0 model the most. For this simulation, they report that a powerful and time-varying jet is produced, while the jet power in our a09rc0 model is relatively weak in the quasi-steady phase. We note that the two models have different initial gas and magnetic field configurations. More importantly, the accretion flows in the two models have been evolved for significantly different periods, which likely has led to the discrepancy between the results. The Ressler et al. (2021) simulation has run up to only $t \sim 20000 \, r_g/c$, during which period the accretion flow in our a09rc0 model is also in the MAD state, while the magnetic flux decreases to below MAD level in later phases. More analysis is shown in Appendix B.

Furthermore, Kaaz et al. (2022) have studied the BHL accretion of magnetized accretion onto a BH traveling through a uniform magnetized medium. Their B100R53 model has the most analogous configuration to our a09rc0 model with similar black hole spin parameters. In addition, this run has a similar magnetic field strength in the wind compared to our initial disk. Their simulation produces a sporadic jet, which is in good accordance with our results. While their simulations with stronger initial magnetic field strength in the wind can lead to sustained MAD accretion flow, there are some fundamental differences between their setting and ours: First, there is a steady supply of magnetic flux from the medium that the black hole is traveling through in their simulations. Second, the relative motion between the black hole (and its accretion disk) and the surrounding medium might help retain the magnetic flux in a similar way as in our a09rc50 model.

#### 4.2. Applications to various black hole accretion systems

In this section, we will briefly discuss how our results are relevant for a few black hole accretion systems in which the accretion flows are believed to have very low specific angular momenta.

**Sgr A*: Sgr A*, the SMBH in the nuclei of our Galaxy, has a very low luminosity $L_{\text{bol}} \lesssim 10^{46} \text{erg s}^{-1}$ (Narayan et al. 1998; Bower et al. 2019), indicating that it hosts a radiatively inefficient accretion flow (see a review by Yuan & Narayan 2014). Linear polarization measurements of Sgr A* also constrains the accretion rate to be as low as $10^{-9} - 10^{-7} M_\odot \text{yr}^{-1}$ near the horizon (e.g. Marrone et al. 2006). The accreting gas is likely supplied by the stellar wind...
Figure 5. Leakage of magnetic flux: The panels show snapshots at $t = 35000r_g/c$ in the a09rc0 model (top four panels) and a09rc50 model (lower four panels) in the vertical plane (panels a and c) and equatorial plane (panels b and d). The left column shows the gas density, and the right column shows the electromagnetic energy flux. The inflow regions are shaded with a light blue color, with blue contours marking the inflow-outflow boundaries. The pink contours indicate the jet boundaries with $\sigma = 1$. The black lines in the left column are the density-weighted velocity streamlines, and the white lines in the right column are the magnetic field lines. One can see that in the a09rc0 model gas around the mid-plane can persistently flow out at a large range of angles and carry away large magnetic fluxes. In contrast, in the $R_c = 50r_g$ run, more steady inflow structure can form, which likely plays an important role in retaining the high level magnetic flux in the inner accretion flow. (Full movies of these models can be seen at https://tomkm.com/madbondi.html.)
from the neighboured WR stars, which gives low cumulative angular momentum (e.g., Quataert 2004). Continuous accretion of stellar winds together with their magnetic fields is sufficient to form a normal MAD flow as shown by numerical simulations (Ressler et al. 2020). Furthermore, the recent Event Horizon Telescope observation of Sgr A* favors the model that Sgr A* is rapidly spinning and surrounded by a prograde accretion disk (The Event Horizon Telescope Collaboration et. al. 2022).

The findings above imply that our simulations of magnetized, Bondi-like accretion flow are very relevant for interpreting the properties of Sgr A*. For example, suppose we take the accretion rate of $10^{-9} - 10^{-7} M_\odot \text{yr}^{-1}$ constrained from observation and use the minimum jet efficiency of about 10% from our simulated accretion flow with zero angular momentum, we obtain a total jet power of $10^{36} - 10^{38} \text{erg s}^{-1}$, which is large enough to power Sgr A* radio and X-ray emission, which has the isotropic luminosity of at most $10^{35} \text{erg s}^{-1}$ at radio and X-ray wavelengths (Morris & Serabyn 1996; Baganoff et al. 2003). Future higher-resolution observations and simulations/modeling of this type can allow us to better constrain the accretion flow structure and jet properties in Sgr A*.

**Long GRBs:** The emergence of long GRBs is usually explained using the collapsar model. In a collapsar, the core of a massive star has collapsed and formed a spinning BH, while the stellar envelope material is still accreting onto the BH, which launches a powerful, relativistic jet (Woosley 1993). However, there is a debate whether the envelope of the progenitor star could have insufficient angular momentum to form a normal accretion disk (e.g., MacFadyen & Woosley 1999). Interestingly, our simulations show that even non-rotating accretion flows can still launch a jet that is powerful enough to be the central engine of a long GRB, which alleviates the problem, although the black hole still needs to acquire enough angular momentum during the initial collapsing process to gain a large spin.

**TDEs:** In TDEs, a star is tidally disrupted by a supermassive black hole (SMBH) along a parabolic orbit. Interestingly, the circularization radius of the stellar debris is usually a few tens of $r_g$ for typical stellar and black hole parameters (Rees 1988). Therefore, our work shows that the TDEs accretion flows have the critical angular momentum needed to form MADs, if sufficient magnetic fields are supplied to the gas. Indeed, three TDEs have been observed to produce highly-beamed X-rays, which are believed to be powered by jets (e.g., Bloom et al. 2011; Zauderer et al. 2013; Tchekhovskoy et al. 2014), which is consistent with our prediction that accretion flow with such angular momentum can still reach the MAD condition and launch strong, relativistic jets. The majority of TDEs, however, produce thermal-like emissions likely associated with the disks or winds (Dai et al. 2018; Gezari 2021). This suggests that either most dormant SMBHs do not possess large spins or most TDEs lack sufficient magnetic fluxes to form MADs.

**Wind-fed BH HMXBs:** High-mass X-ray binaries (HMXBs) are often wind-fed systems instead of going through Roche-lobe overflow. In such a system, the accretion flow around the compact object forms from the capture of the wind from the donor giant star and therefore likely has a low specific angular momentum (Shapiro & Lightman 1976). Interestingly, all dynamically confirmed BH-HMXBs have BH spin values near the maximum (e.g., Liu et al. 2008; Gou et al. 2009). In addition, collimated, relativistic jets have been observed from some BH-HMXBs (e.g., Cyg X-1, Stirling et al. 2001). While the full hydrodynamics of wind-fed accretion can be complicated, our simulations of simplified Bondi-like accretion show that indeed powerful jets can be formed from these systems if there has sufficient magnetic fluxes. Future observations of the jet power might even allow us to constrain the spins of BHs in HMXBs.

### 5. SUMMARY

In this work, we have performed novel 3D GRMHD simulations of a magnetized Bondi-like accretion flow around a rapidly spinning black hole. The three models have different initial specific angular momenta ranging from zero to a small value corresponding to that of a Keplerian disk circularized at $50r_g$. The simulations results highlight the role that initial gas angular momentum plays in forming MADs and producing powerful jets. We summarize the main findings as follows:

1. Even a Bondi accretion flow with zero gas angular momentum around a rapidly spinning BH can still launch a relativistic jet magnetically. However, the jet tends to be intermittent, wobbly, and relatively weak. The jet power can reach about ten percent of the accretion power.

2. For forming a very powerful and stable jet, the accretion flow has to achieve and sustain the MAD state, which requires a critical specific angular momentum of the accretion flow. However, the threshold is very small, which corresponds to a circularization radius between $10r_g$ and $50r_g$. Under such circumstances, the jet efficiency can approach and sometimes exceed 100%.
3. When the angular momentum of the accretion flow does not reach this critical value, the accretion inflow is unsteady even close to the black hole. Gas can have different rotation directions at different inclinations. Furthermore, gas can flow in along certain azimuthal angles around the mid-plane but persistently flow out to large radii at other azimuthal angles. These outflow regions contain a large amount of magnetic fluxes, providing a channel for them to leak out. As a result, the accretion flow cannot sustain the MAD state.

4. In contrast, when the threshold of specific angular momentum has been reached, a more steady accretion inflow structure can form around the black hole with coherent rotation and persistent inflow along the mid-plane in the inner region. Therefore, less magnetic fluxes leak out, and we suspect that the rotating gas inflow can further shred any outflowing magnetic bubbles and bring back some of the magnetic fluxes contained in them. This allows the MAD condition to be reached and sustained.

We emphasize that we have only tested the simplified scenario where the gas angular momentum, black hole spin and magnetic field axes are all aligned, while the realistic configurations can be more complicated. Furthermore, the treatment of cooling and radiative processes can be improved by conducting simulations using codes incorporating radiative transfer physics, which is particularly important in the super-Eddington accretion regime. Nonetheless, this work has disclosed that accretion flows around spinning black holes only need to possess small specific angular momenta to become MADs and launch very powerful jets. The results have important consequences for understanding various black hole accretion systems with low gas angular momentum, such as Sgr A* and other low-luminosity AGNs, TDEs, GRBs and certain HMXBs, and in particular, what sets the jet power in such systems.

We thank S. Woosley for useful discussions. TK and LD acknowledge the support from the Hong Kong Research Grants Council (HKU27305119, HKU17305920) and the National Natural Science Foundation of China (HKU12122309). We acknowledge the computational support from NSF via XSEDE resources and from the supercluster and the HPC computing facilities offered by ITS at HKU and the Tianhe-2 supercluster.

APPENDIX

A. SIMULATION INITIAL SETUP AND PARAMETERS

We conduct three simulations with different initial gas specific angular momenta. In each simulation, the maximum specific angular momentum of the gas is set by the characteristic specific angular momentum at the circularization radius calculated using Eqn. 11, with $R_c = 0$, 10, or 50 $r_g$ respectively. For our chosen magnetic flux distribution, a magnetic field line passing through a point $(r_0, \theta_0)$, with $\Psi = \Psi_0 \equiv \Psi (r_0, \theta_0)$, will cross the equatorial plane at the “footpoint” radius of

$$R_{fp} = r_0(1 - |\cos \theta_0|).$$  \hspace{1cm} (A1)

The initial specific angular momentum distribution is set as:

$$l = \begin{cases} 
    l_{\text{max}} & \text{for } R_{fp} > R_{\text{solid}} \\
    l_{\text{max}} \times \frac{R_{fp}^2}{R_{\text{solid}}^2} & \text{for } R_{fp} \leq R_{\text{solid}}
\end{cases}$$  \hspace{1cm} (A2)

where $R_{\text{solid}} \equiv 100r_g$ and $R_{fp}$ is given by Eqn. A1. Using this setup, close to the black hole, gas rotates approximately as a solid body (i.e., $u^\phi$ is roughly constant), so we avoid having a nonphysically high specific angular momentum. Also, outside the equator, the value of $l$ is propagated along the magnetic field lines. We plot the initial specific angular momentum, together the the magnetic field lines, in Fig. A.1.

A few numerical and physical parameters of the simulations are listed in table A.1. Besides various parameters discussed in the main text, we further show the value of $s$, the BH dimensionless spin-up parameter, which is defined as:

$$s \equiv \frac{\text{d}j}{\text{d}t} \frac{M_{\text{BH}}}{\langle M_H \rangle t} = -j - 2a(1 - \eta)$$  \hspace{1cm} (A3)
Effect of Gas Angular Momentum on the Jet Launching

Figure A.1. The initial conditions of the gas specific angular momentum $l$ and magnetic field of the three runs (a) a09rc0; (b) a09rc10; (c) a09rc50, respectively. The color shows the initial specific angular momentum. The black lines indicate the initial magnetic field lines.

where $j = \int \frac{T^\phi dA_{\phi}}{(M_H)_r}$ is the specific angular momentum flux of the BH. Positive values indicates the spin-up of the BH.

We can see in all three runs the jet has extracted rotation energy from the BH.

Table A.1. Parameter Summary of the simulations

| Model   | $R_c$ ($r_g$) | $N_r$ | $N_\theta$ | $N_\phi$ | $\phi_H$ | $\eta_H$ (%) | $\eta_j$ (%) | $\eta_{EM}$ (%) | $s$ |
|---------|---------------|-------|-------------|-----------|-----------|---------------|---------------|-----------------|-----|
| a09rc0  | 0             | 288   | 128         | 64        | 26.8      | 19.9          | 17.1          | 13.0            | -12.0 |
| a09rc10 | 10            | 240   | 128         | 64        | 23.2      | 10.8          | 9.8           | 6.8             | -10.5 |
| a09rc50 | 50            | 280   | 128         | 64        | 45.1      | 76.1          | 61.7          | 52.6            | -35.2 |

B. HISTOGRAM OF MAD PARAMETER

Fig. B.1 shows the histograms of the instant dimensionless magnetic flux $\phi_H$ in all snapshots of the three runs, either over the early phase of $t = (0 - 20000)r_g/c$ or over the late phase of $t = (20000 - 50000)r_g/c$. The accretion flow has established inflow equilibrium out to $r \gtrsim 200r_g$ only in the late phase, during which period we have evaluated the results.

One can see that the accretion flow has distinct properties at early and late phases. For model a09rc0 and a09rc10, the inner accretion flow are MAD or nearly MAD before $t \sim 20000$ with $\phi_H$ varying around 40. However, the magnetic flux decays with time and the accretion flow is no longer MAD in the quasi-equilibrium phase. Model a09rc50 shows an opposite behavior. The MAD state is slowly developed and then maintained in the quasi-equilibrium phase.

These results demonstrate the importance of conducting GRMHD simulations for a sufficiently long duration and probably explains some differences in the results obtained by Ressler et al. (2021) and this work.

REFERENCES

Abramowicz, M. A., Czerny, B., Lasota, J. P., & Szuszkiewicz, E. 1988, ApJ, 332, 646, doi: 10.1086/166683

Baganoff, F. K., Maeda, Y., Morris, M., et al. 2003, ApJ, 591, 891, doi: 10.1086/375145
Figure B.1. The histogram of the dimensionless magnetic flux $\phi_H$ around the horizon $\phi_H$ of the three models: (a) a09rc0, a09rc10 and a09rc50. We sample $\phi_H$ in the two different time ranges: 1) The early phase $t = (0 - 20000) r_g/c$, plotted in red, and 2) the late, quasi-equilibrium phase $t = (20000 - 50000) r_g/c$ (when we computed the averaged values of the quantities), plotted in blue. The orange and green dashed-dot lines are the log-normal distribution functions fitting on the profiles of $\phi_H$ in the early and late phases respectively.
