NUMERICAL STUDY OF MAGNETICALLY DOMINATED JETS FROM ACCRETING BLACK HOLE SOURCES*

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We investigate the properties of the magnetically dominated jets from accreting black hole sources. We run the numerical simulation in a 3D general relativistic magneto-hydrodynamic setup and we study the connection between the properties of the jet and the accretion disk. We focus on the formation of magnetically arrested disk state.

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1. Introduction

Accreting black holes act as the central engines of various observed astrophysical phenomena such as gamma-ray bursts, quasars, and blazars. The multi-wavelength observations of the accretion systems show different kinds of outflows. The collimated outflows usually referred to as jets are sites of emission of high-energy photons with spectral energy distribution peaking in the gamma-ray band and characterized by a rapid variability (see [1] for a review about GRBs, and [2] for a discussion of blazar samples observed by SWIFT). Strong gravity acts on the accreting material in such systems due to the presence of a compact central object. The central object can either be a neutron star, a stellar mass black hole (~ 3 to $20 M_{\odot}$, in the case of black hole X-ray binaries or gamma-ray bursts), or a super-massive black hole ($\sim 10^5$ to $10^{10} M_{\odot}$, in the case of active galactic nuclei). Relativistic jets are believed to be powered by the Blandford–Znajek mechanism [3], which can extract the rotational energy of the black hole. This mechanism requires a poloidal magnetic field built up in the vicinity of the black hole due to continuous accretion.

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Jets in Active Galaxies and GRBs are powered by accretion of magnetized plasma. Charged particles gyrate around the magnetic field lines and produce synchrotron radiation. The strength of magnetic field depends on various environmental factors in the vicinity central engine. The turbulence in accretion flows can result in the magneto-rotational instability (MRI) [4], which transports angular momentum outwards in the disk and effectively drives accretion.

On the other hand, if the plasma is threaded by a large-scale magnetic field, the inflow of matter to the central engine can be affected in a different way. This can occur due to a variety of reasons, such as dragging the external magnetic field with the flow, or the field inheritance from the past history of the progenitor or host. In such cases, the central object accumulates a large amount of poloidal flux as the accretion proceeds. The accumulated flux cannot fall into the black hole, only matter can fall in. This flux cannot escape either, due to the inward pressure of accretion. The structure is then regulated by the interchange instabilities. Thus, the infalling matter is arrested due to the action of magnetic fields and further accretion is only possible in shorter episodes. Such a state is often termed as the magnetically arrested disk (or MAD) [5, 6].

Numerical simulations have been performed by many groups to understand the evolution of such accretion flows. They typically adopt an initial equilibrium torus embedded in a magnetic field which causes turbulence. Instabilities develop with time and thus the accretion proceeds. The initial magnetic field topology determines the evolution of the flow. If the initial field does not allow significant flux accumulation onto the black hole, the accretion proceeds without much hindrance (see [7]). Such a configuration is called standard and normal evolution (SANE) in contrast to the MAD state. For achieving the MAD state, the simulation must enforce a substantial accumulation of magnetic flux over time.

2. Numerical modelling

2.1. Code

In order to study the formation and evolution of jets, we compute the structure and evolution of a black hole accretion torus by evolving the general relativistic magnetohydrodynamic (GRMHD) equations in time. We use the HARM (High Accuracy Relativistic Magnetohydrodynamics) code [8] which is a conservative and shock-capturing scheme. The numerical scheme advances the conserved quantities from one time step to the next by solving a set of non-linear equations, in each time step. We follow the flow evolution by solving numerically the continuity, energy-momentum conservation, and induction equations in the GRMHD scheme

$$\nabla_\mu(\rho u^\mu) = 0\,, \qquad \nabla_\mu(T^{\mu\nu}) = 0\,, \qquad \nabla_\mu(u^\nu b^\mu - u^\mu b^\nu) = 0\,, \tag{1}$$

$$T^{\mu\nu} = T^{\mu\nu}_{\rm gas} + T^{\mu\nu}_{\rm EM}\,, \tag{2}$$

$$T^{\mu\nu}_{\rm gas} = \rho h u^\mu u^\nu + p g^{\mu\nu} = (\rho + u + p) u^\mu u^\nu + p g^{\mu\nu}\,,$$

$$T^{\mu\nu}_{\rm EM} = b^2 u^\mu u^\nu + \tfrac{1}{2} b^2 g^{\mu\nu} - b^\mu b^\nu\,, \qquad b^\mu = u^*_\nu F^{\mu\nu}\,. \tag{3}$$

Here, the stress-energy tensor is comprised of the gas and electromagnetic terms, u^μ is the four-velocity of the gas, u is the internal energy, ρ is the density, p is the pressure, and b^μ is the magnetic four-vector. F is the Faraday tensor and in a force-free approximation, we have $E_\nu = u^\nu F^{\mu\nu} = 0$. The unit convention is adopted such that $G = c = M = 1$ and thus the black hole mass will scale the simulations (*e.g.* gravitational radius $r_{\rm g} = GM_{\rm BH}/c^2$ or time $t_{\rm g} = GM_{\rm BH}/c^3$).

2.2. Simulation setup

Our initial condition for the simulation assumes a pressure equilibrium torus as described by Fishbone and Moncrief [9]. In this solution, the angular momentum along the radius of the disk is a constant. We ran our simulation with initial poloidal loops of sufficiently high strength with the intention of eventually forming a MAD state. Since we choose a purely poloidal field, the only non-zero component of the vector potential is given by $A_\phi = r^5(\rho_{\rm avg}/\rho_{\rm max} - \rho_0)$, which has a dependence on the disk density structure as well as a power of radius. The imposed poloidal magnetic field lines affect the stable solution and result in turbulence within the disk. This turbulence causes the MRI to develop and thus causes the accretion of the matter to start. We use the plasma β parameter, which is defined as the ratio of the gas-to-magnetic pressure, $\beta = p_{\rm gas}/p_{\rm mag}$, to scale the strength of the magnetic field. Here, $p_{\rm gas} = (\gamma - 1)u_{\rm max}$ and $p_{\rm mag} = b^2_{\rm max}/2$, where $u_{\rm max}$ is the internal energy of the gas at the radius of maximum pressure. We normalize β to a value 50 at the radius of maximum gas pressure, $r_{\rm max}$ inside the torus.

In our model, we use a polytropic equation of state, $p_{\rm g} = K\rho^\gamma$, where $p_{\rm g}$ is the gas pressure, ρ is the density, and K is the constant specific entropy. We use the value of 4/3 for the polytropic index γ.

We study our model with the Kerr parameter $a = 0.90$. We run the complete simulation in 3D with a resolution of $288 \times 256 \times 64$ in the r, θ, and ϕ directions, respectively. The outer edge of the grid is located at 10^5 gravitational radii. The initial size of the disk is prescribed using the inner edge of the disk and the radius of pressure maximum, and they have the values $r_{\rm in} = 6$ and $r_{\rm max} = 13.5\,r_{\rm g}$, respectively. Figure 1 (a) shows the initial state of the disk embedded in a poloidal magnetic field.

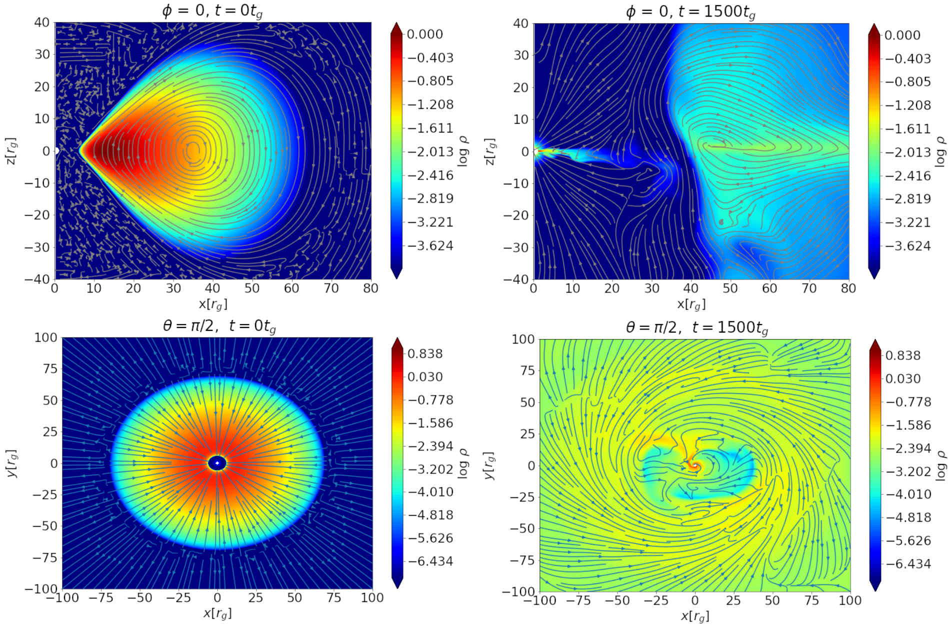

Fig. 1. The initial and evolved states of density at time $t = 0$ and $t = 1500\, t_{\mathrm{g}}$ respectively, along with streamlines of the magnetic field. The plots (a) and (b) show the snapshots along a poloidal slice and the plots (c) and (d) show the snapshots along the equatorial slice.

3. Results

The accretion flow is started by the influence of the poloidal magnetic field on the initial steady state solution. The turbulence in the plasma caused by the magnetic field results initially in the MRI and the matter starts falling inward to the central object due to the transport of angular momentum to the outer regions of the disk. But as time proceeds, the accreting plasma brings in more poloidal magnetic flux to the central object. This flux cannot go into the black hole and instead it gets accumulated in its vicinity. After some time, this accumulated flux hinders with the accretion and the disk gets arrested. This is evident from Fig. 1 (b) where the disk is not able to accrete smoothly due to the presence of the strong poloidal magnetic field. Thus, our simulation results in a magnetically arrested disk, around $1500\, t_{\mathrm{g}}$.

In Fig. 2 (a), we plot the total magnetic flux on the black horizon Φ_{BH}, normalized to the mass flux, to see the building up of the magnetic flux in the vicinity of the black hole. It can be seen from the plot that the magnetic flux at the horizon is 10 times or more higher than the inward mass flux after a certain time. The further accretion in such a disk is possible through interchange instability inside the plasma.

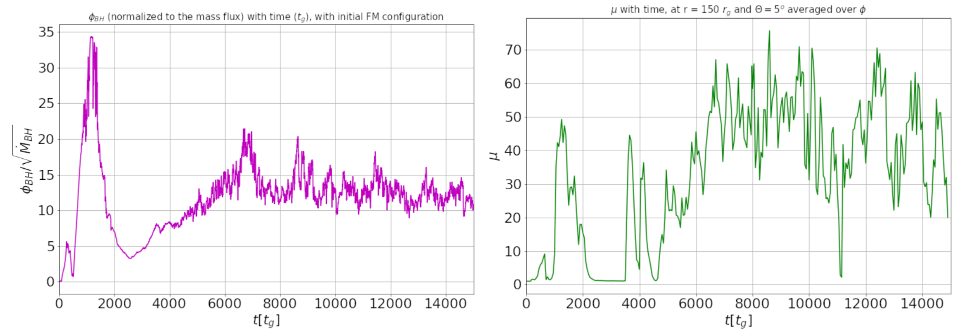

Fig. 2. (a) The time evolution of the magnetic flux at the black hole horizon normalized to the mass flux, defined as: $\Phi_{\rm BH} = \frac{1}{\sqrt{\dot{M}}} \int \mid B^r(r_{\rm hor}) \mid {\rm d}A_{\theta\phi}$. (b) The jet energetic parameter μ with time (in $t_{\rm g}$) at a chosen point $r = 150\, r_{\rm g}$ and $\theta = 5°$ averaged over the whole ϕ range.

We investigate the evolution of the jet by studying the jet energetics parameter

$$\mu = -T^r_t/\rho u^r \tag{4}$$

which is the total plasma energy flux normalized to the mass flux, where, T^r_t is the energy component of the energy-momentum tensor, ρ is the gas density, and u^r is the radial velocity. Figure 2 (b) shows the time evolution of the jet energetics parameter μ at a chosen point and Fig. 3 shows the distribution of μ at two different time snapshots along two different ϕ slices. It can be observed from these plots that the jet emission is not continuous but intermittent. It is noteworthy that such a jet emission is observed along with the MAD state where the accretion proceeds in short episodes rather than a continuous flow of matter to the central object.

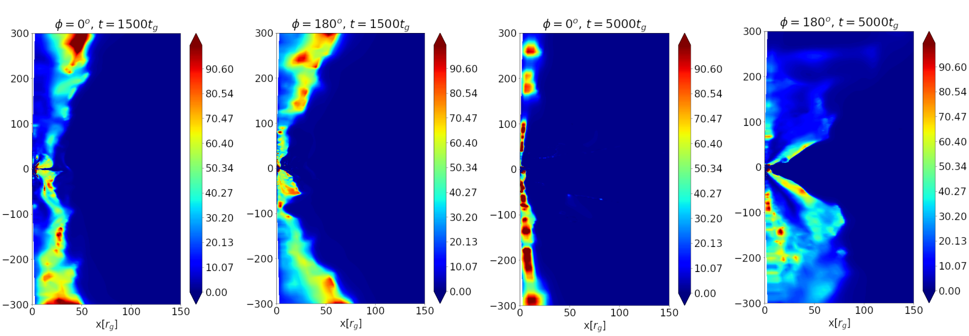

Fig. 3. The distribution of the jet energetics parameter μ at $t = 1500$ and $5000\ t_{\rm g}$, respectively, along the $\phi = 0°$ and $180°$ slices, respectively.

4. Conclusions

In this study, we extended our previous 2D axisymmetric simulations to cover the 3D structure and non-axisymmetric evolution of the disk–jet system. We observed the formation of the MAD state due to the accumulation of large magnetic flux on the black hole horizon. The normalized magnetic flux can be as high as 20 and remains higher than 10 for the most part of the simulation. Similarly to the 2D simulation results [10] the jet emission is episodic rather than continuous after the formation of the MAD state. However, the magnetic flux decayed much faster (after $\sim 4000\, t_{\mathrm{g}}$) in our 2D setup. The non-axisymmetric evolution of the system helps us to model the accretion flow in a more realistic manner where the magnetic field in the torus is not decayed. In axisymmetric models, the accretion can be halted completely, and only a transient equatorial current sheet can form. In 3D models, a larger spectrum of Rayleigh–Taylor instability modes can develop, and thus the turbulence in the disk is sustained for a longer duration. Hence, this setup is a plausible candidate for studies of long GRBs.

In the future work, we plan to investigate the influence of different initial states on the evolution of the system and to make a quantitative analysis of time variability.

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