Black hole outflows initiated by accretion of large-scale magnetic field

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ABSTRACT

Black holes attract gaseous material from the surrounding environment. Magnetic pressure acts against accretion and it can lead to the magnetically arrested state. The black hole does not hold the magnetic field by itself: once the accretion rate diminishes, the magnetic field lines can push the plasma clumps away from the black hole. We examine an example of an outflow driven by a large scale magnetic field. To this end, we initiate the computations with an axially symmetric configuration of a uniform magnetic field aligned with the common rotation axis of the black hole. Then we evolve the initial configuration in the force-free limit. We observe how the magnetic lines of force start accreting with the plasma while an equatorial intermittent outflow develops and goes on ejecting some material away from the black hole.

INTRODUCTION

Various observational studies point towards the idea that an accreting black hole acts as the central engine of astrophysical objects such as active galactic nuclei (AGN) and gamma-ray bursts. The accretion of plasma onto the central compact object due to its gravitational force produces various observable effects including the relativistic jets and outflows in the form of winds. It is appropriate to assume that plasma at large-scales is magnetized due to its environment. In this work we focus on the equatorial outflows in an accreting plasma around a central black hole mediated by the presence of large-scale magnetic fields. We base this work on the article (V. Karas et. al. 2020) [1] which discusses the equatorial outflows driven by large-scale initially uniform magnetic fields. Such outflows are recently considered to explain the observed properties of M87*, with an in-fall of matter at a larger radius and an ejection disc at a smaller radius [2]. In this work we are interested in gradually evolving the structure of the magnetic field and mass flow in the regions near to the black hole horizon in the presence of a large-scale uniform magnetic field (Wald, 1974) [3]. We use an initially spherically symmetric inflow, given by the Bondi (1952) solution [4], as the initial stationary solution and evolve it with time.

NUMERICAL SETUP

We model accretion onto a black hole in a fixed Kerr metric. The solution can be written in terms of the metric element

$$ds^2 = -\frac{\Delta\Sigma}{A}dt^2 + \frac{\Sigma}{\Delta}dr^2 + \Sigma d\theta^2 + \frac{A sin^2\theta}{\Sigma}(d\phi - \omega dt)^2 \quad (1)$$

in Boyer-Lindquist coordinates, where $\Delta(r) = r^2-2r+a^2$, $\Sigma(r, \theta) = r^2 + a^2 \cos^2 \theta$, $A(r, \theta) = (r^2 + a^2)^2 - \Delta a^2 \sin^2 \theta$, $\omega(r, \theta) = 2ar/A(r,\theta)$. We consider an axially symmetric case and limit ourselves now to 2D evolution. We use our version of the HARM code [5][6], an ideal MHD case in which the field lines are frozen into the plasma, to evolve the equations of magnetohydrodynamics. We use the dimensionless spin parameter a to quantify the black hole rotation. The code works in natural units with G=c=M=1 so that the velocities become dimensionless and the lengths and times can be measured in units of the black hole mass M (so the lengths will be units of $r_g = GM/c^2$ and time in $t_g = GM/c^3$).

We initialize our models with a purely radial and spherically symmetric inflow of matter prescribed by the well known Bondi solution. The sonic point for this flow is set at 80 r_g . To initiate the simulations, we employ an initially uniform Wald magnetic field which can be fully described by the only non-vanishing components of the vector potential:

$$A_t = B_0 a[r\Sigma^{-1}(1 + cos^2\theta) - 1] \quad (2)$$

$$A_\phi = B_0[\tfrac{1}{2}(r^2 + a^2) - a^2 r\Sigma^{-1}(1 + cos^2\theta)]sin^2\theta \quad (3)$$

in Boyer-Lindquist coordinates where B_0 is the intensity of the uniform magnetic field far from the event horizon, and given a constant value. The idealized initial configuration rapidly evolves to a complex structure once the accretion begins, with more turbulent field lines in the accreting region and a bit more organized field lines in the empty funnel regions close to the black hole rotation axis. As the system evolves, a fraction of the material put spherically at the outer boundary of the grid remains bound and it forms an accretion disk associated with the black hole.

We set the outer boundary of our computational grid at the radius 10^3 r_g, where the inflow is purely radial initially. The inner boundary is set at 0.87 * r_{hor} where r_{hor}= 1+ $\sqrt{(1 - a^2)}$ is the radius of the event horizon. The grid domain is set to the resolution of 512x512 in the r and θ directions respectively and the adiabatic index is set to $\gamma = 4/3$ in our models. We normalize the maximum value of the plasma β parameter defined as the ratio of gas to magnetic pressure, i.e. its value nearest to the horizon, to set the strength of the magnetic field. We study the case with a high magnetization setting the maximum value of β in our models to be 0.5. We also study the models with three different spin values a= 0.99, 0.95 and 0.60 to understand its effect on influencing the magnetic field.

CONCLUSIONS

In this work, we focused on the transition between two extreme states of accretion, where a Wald-type uniform initial seed field aligned with the black hole rotation axis comes in contact with a radial Bondi-type mass inflow. The plasma drags the field lines to the black hole horizon, and at the same time become influenced and partly expelled by the evolution of the magnetic field. Our model serves as a test solution that demonstrates the rapid disappearance of magnetic expulsion as the conducting plasma starts to get accreted. As this happens, the magnetic field lines are bent in the radial direction and start to reconnect along the equatorial plane thus accelerating an outflow in a direction perpendicular to the rotation axis of the black hole. We can suggest that such backflows are a generic feature that can occur in different accreting systems.

RESULTS

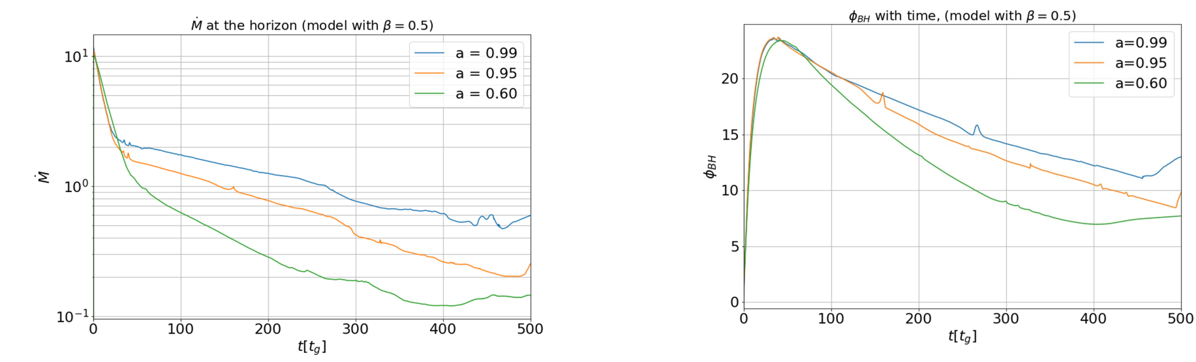

Fig. 2: Time evolution of (a) mass accretion rate at the black hole horizon and (b) magnetic flux on the black hole horizon.

At the initial time t = 0 t_g, the magnetic field lines are expelled from the black hole horizon due to the black hole rotation. But as the accretion begins, the plasma starts to bring in the magnetic flux to the horizon and the field lines start crossing the horizon. This can be seen in Fig. 1 which show the initial and evolved states of the plasma near the black hole horizon for the case of spin a = 0.99. This eventually results in magnetic reconnection events in the equatorial regions of the flow (mainly due to numerical resistivity in the code). This in turn causes the equatorial outflow of the plasma which is illustrated in the middle and bottom rows of Fig. 1. Fig. 2(a) shows the mass accretion rate on the black hole horizon at the initial phase of higher mass accretion, which gets reduced later due to an outflow being developed in the equatorial region.

The magnetic flux on the black hole horizon ϕ_{BH} can be quantified by integrating the radial component of the magnetic field at r_{hor} and its evolution with time is given in Fig. 2(b) showing the initial gradual increase of it to a maximum value and then the decrease due to formation of the current sheet and the reconnection events in the equatorial region of the flow.

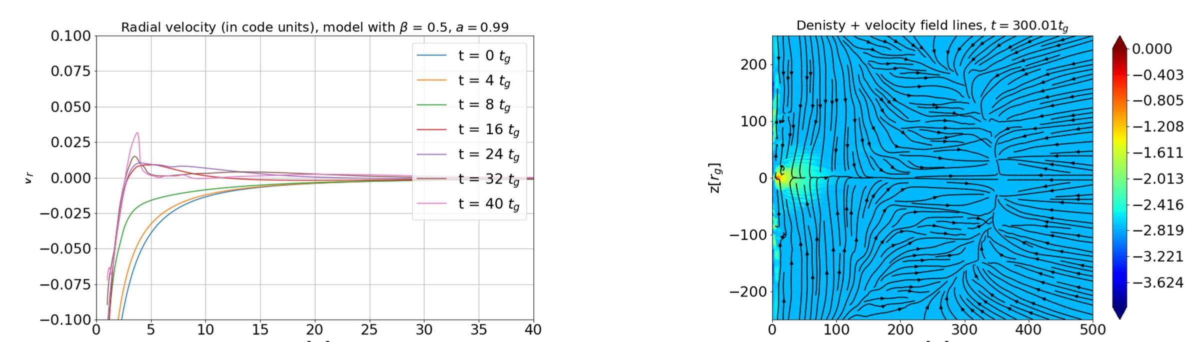

Fig. 3: (a) Radial velocity (v_r) with radius at chosen time steps showing the evolution of velocity along the equatorial region of the flow (b) velocity field lines on top of density contours at a later evolved time showing the radius of the ejection disk, where the outflow reverses to an inward flow.

The right column of Fig. 1 depicts the velocity field lines plotted on top of the density structure at evolved timesteps. This shows the initial pure radial inflow of matter being eventually developed into outflows at the equatorial region as the magnetic reconnection events begin to occur. In Fig. 3(a), we plot the radial velocity with the radius at different time instances up to a radius of 40 r_g at the equator. This shows the evolution of velocity with time and the movement of the outflows with the radius. The outflow velocities are higher in the regions near to the horizon where the reconnection events occur and the blobs move outward eventually but get slower as they move away from the black hole. The radius of the ejection disk at an evolved time, after the inward mass accretion settles into a steady rate, e.g. at t = 300 t, can be estimated to be around 350r_g in our model from the velocity field plot in Fig. 3(b). At this radius the equatorial outflow ends and the flow transforms into an infall of the plasma

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Fig. 1: The color coded initial and evolved density distribution overplotted with the magnetic field lines (left) and the gas velocity flow lines (right).