Magnetically Ejected Disks: Equatorial Outflows Near Vertically Magnetized Black Hole

Vladimír Karas
Astronomical Institute, Czech Academy of Sciences

in collaboration with
Kostas Sapountzis & Agnieszka Janiuk
Center for Theoretical Physics, Polish Academy of Sciences

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Talk dedicated to prof. Zdeněk Stuchlík and his work as a celebration of his 70th birthday

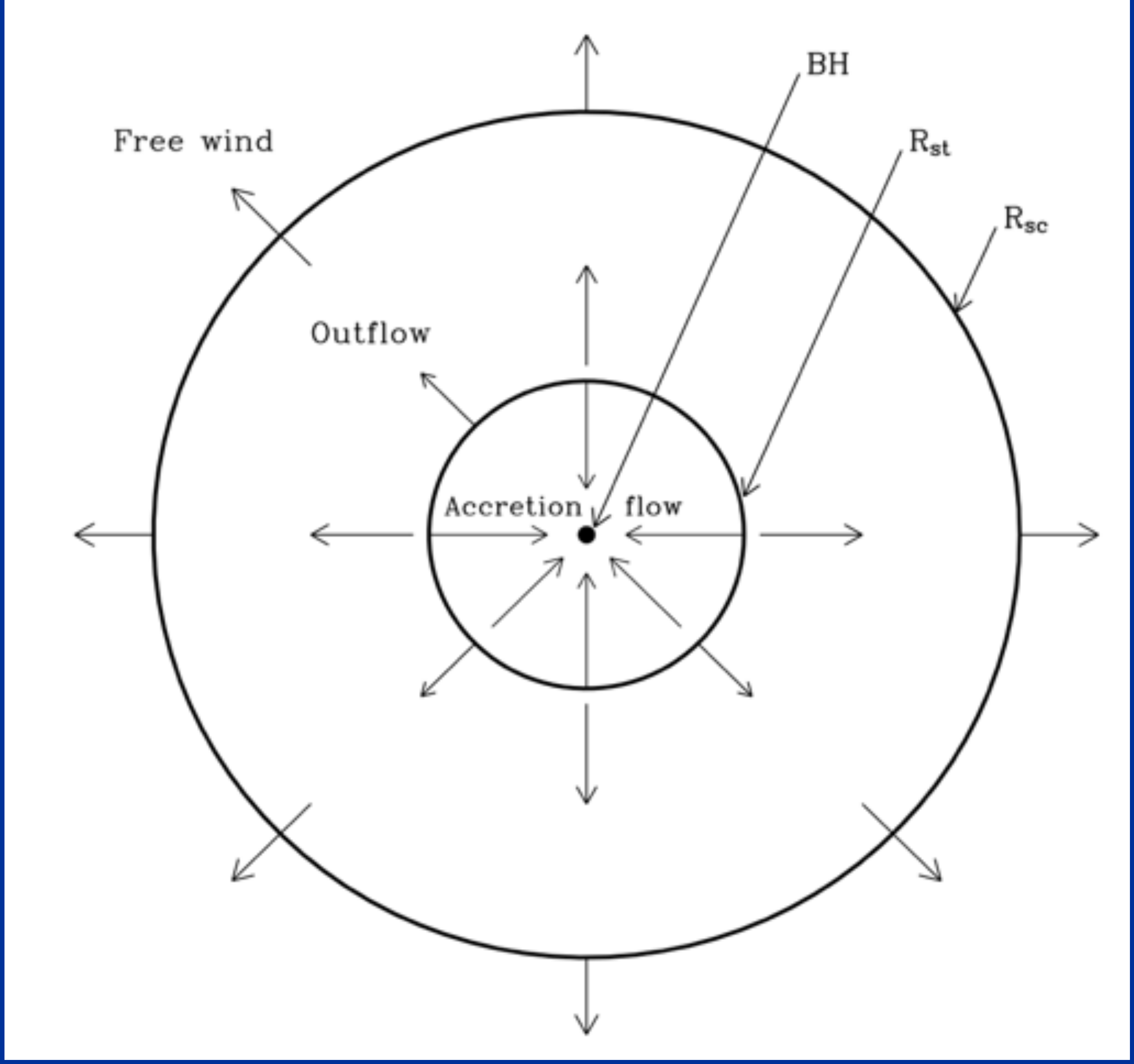
X-ray: NASA/CXC/SAO; Optical: NASA/STScI; Radio: NSF/NRAO/AUI/VLA; VLBI: Boccardi et al. 2017)

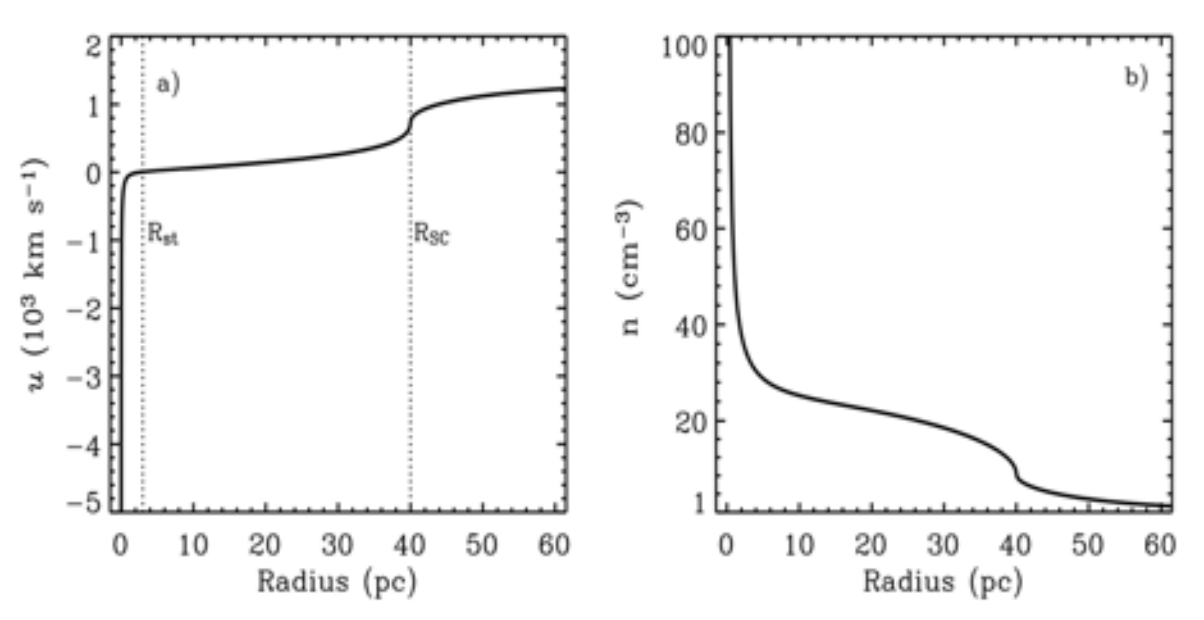
Cygnus A radio galaxy

(Blandford, Meier & Readhead 2017)

The initial set-up

• black hole in vacuum • magnetic field • plasma far away





(Bondi 1952; Silich et al. 2008)

Magnetized rotating black hole

Kerr metric describing the geometry of the spacetime around the rotating black hole is expressed in Boyer-Lindquist coordinates $x^\mu = (t, r, \theta, \varphi)$ as follows (Misner et al. 1973):

$$ds^2 = -\frac{\Delta}{\Sigma}\left[dt - a\sin\theta\, d\varphi\right]^2 + \frac{\sin^2\theta}{\Sigma}\left[(r^2+a^2)d\varphi - a\, dt\right]^2 + \frac{\Sigma}{\Delta}dr^2 + \Sigma d\theta^2, \tag{1}$$

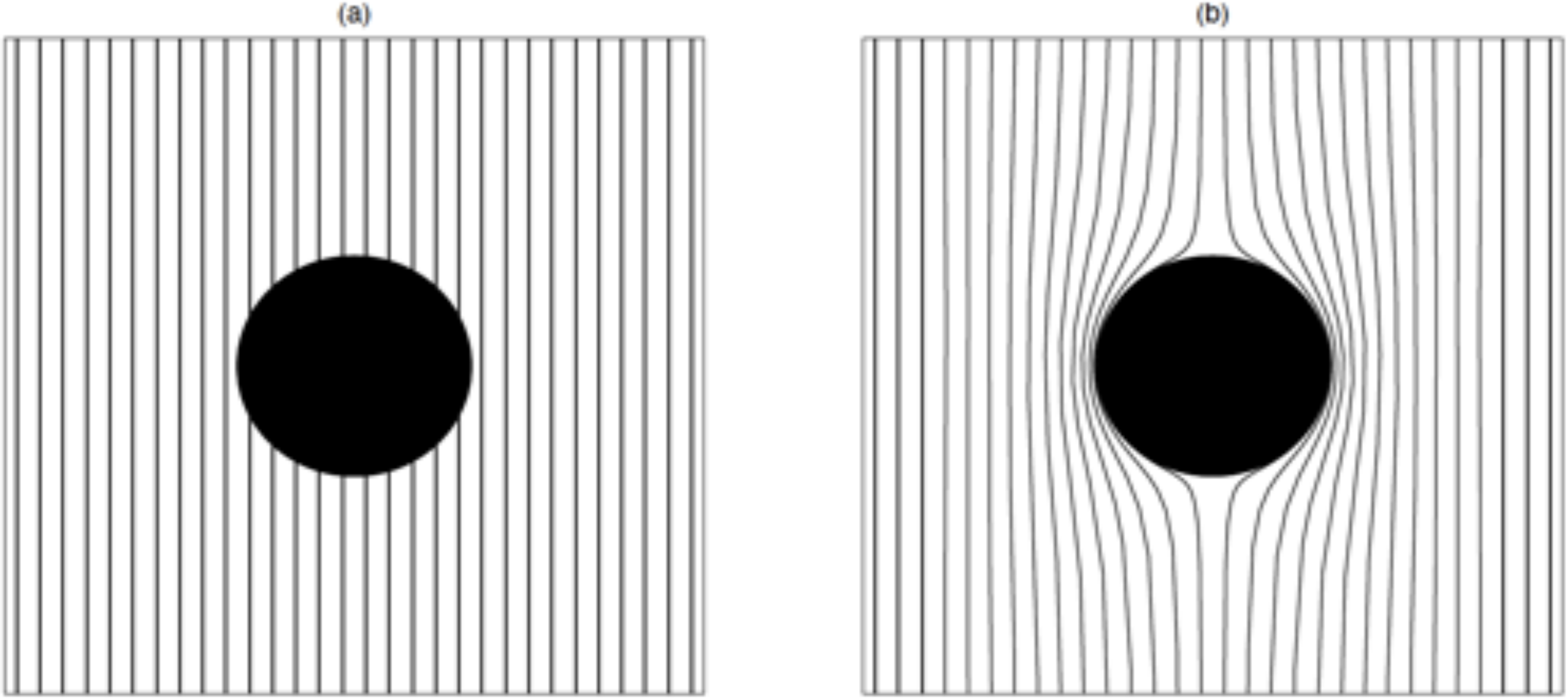
where

$$\Delta \equiv r^2 - 2Mr + a^2, \quad \Sigma \equiv r^2 + a^2\cos^2\theta. \tag{2}$$

Coordinate singularity at $\Delta = 0$ corresponds to outer/inner horizon of the black hole $r_\pm = M \pm \sqrt{M^2 - a^2}$. Rotation of the black hole is measured by the spin parameter $a \in \langle -M, M\rangle$. Here we only consider $a \geq 0$ without the loss of generality.

(Kerr 1963)

Magnetized rotating black hole



An axisymmetric case: (a) $a = 0$ (a static black hole), and (b) $a = M$ (a maximally rotating black hole).

(Wald 1974; Bičák & Karas 1989)

We employ the test-field solution of Maxwell's equations for a weakly magnetized Kerr black hole immersed in an asymptotically uniform magnetic field specified by the component B_z parallel to the spin axis and the perpendicular component B_x. The electromagnetic vector potential A_μ is given as follows (Bičák & Janiš 1985):

$$A_t = \frac{B_z a M r}{\Sigma}\left(1+\cos^2\theta\right) - B_z a + \frac{B_x a M \sin\theta\cos\theta}{\Sigma}\left(r\cos\psi - a\sin\psi\right), \tag{3}$$

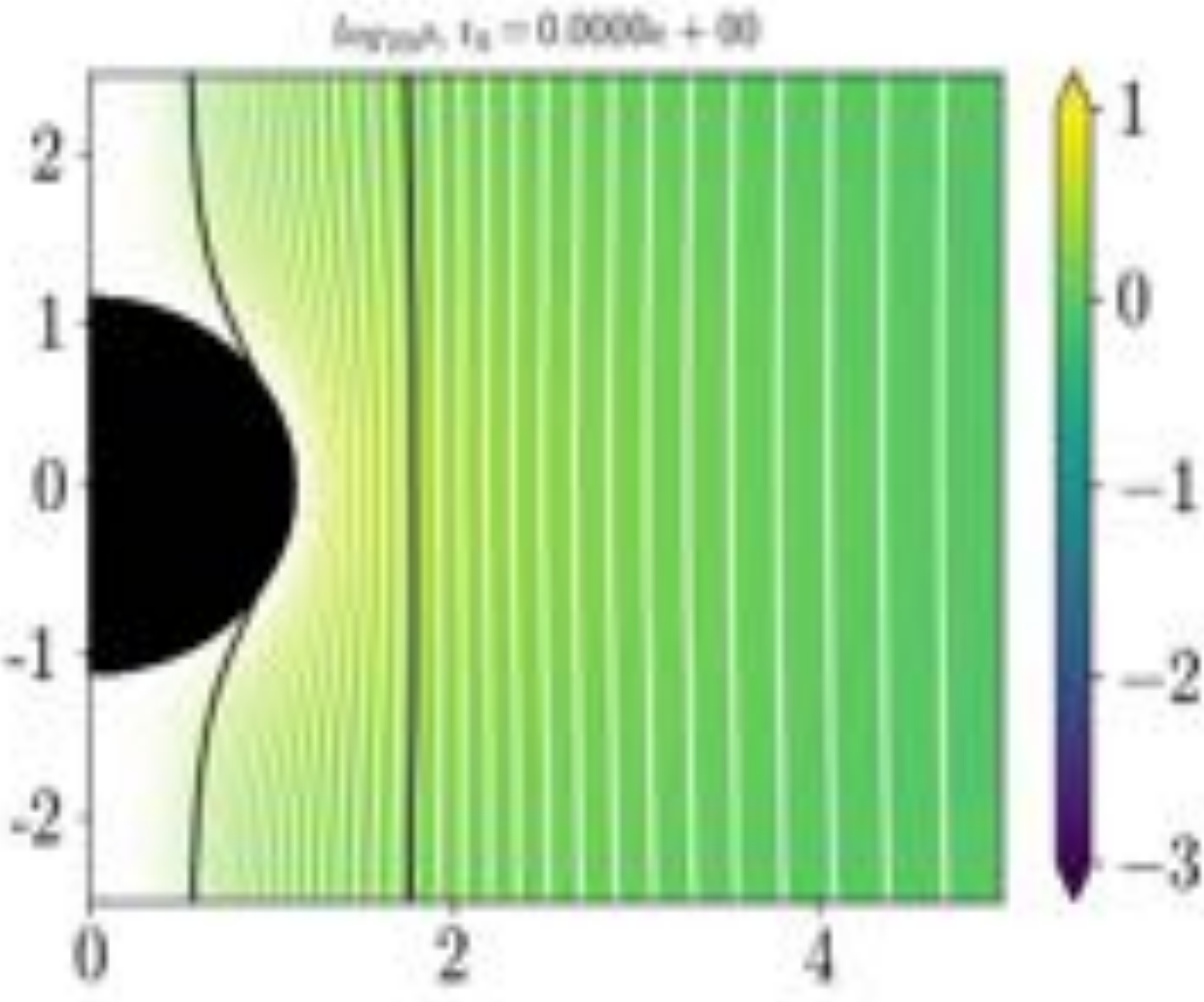
$$A_r = -B_x(r-M)\cos\theta\sin\theta\sin\psi, \tag{4}$$

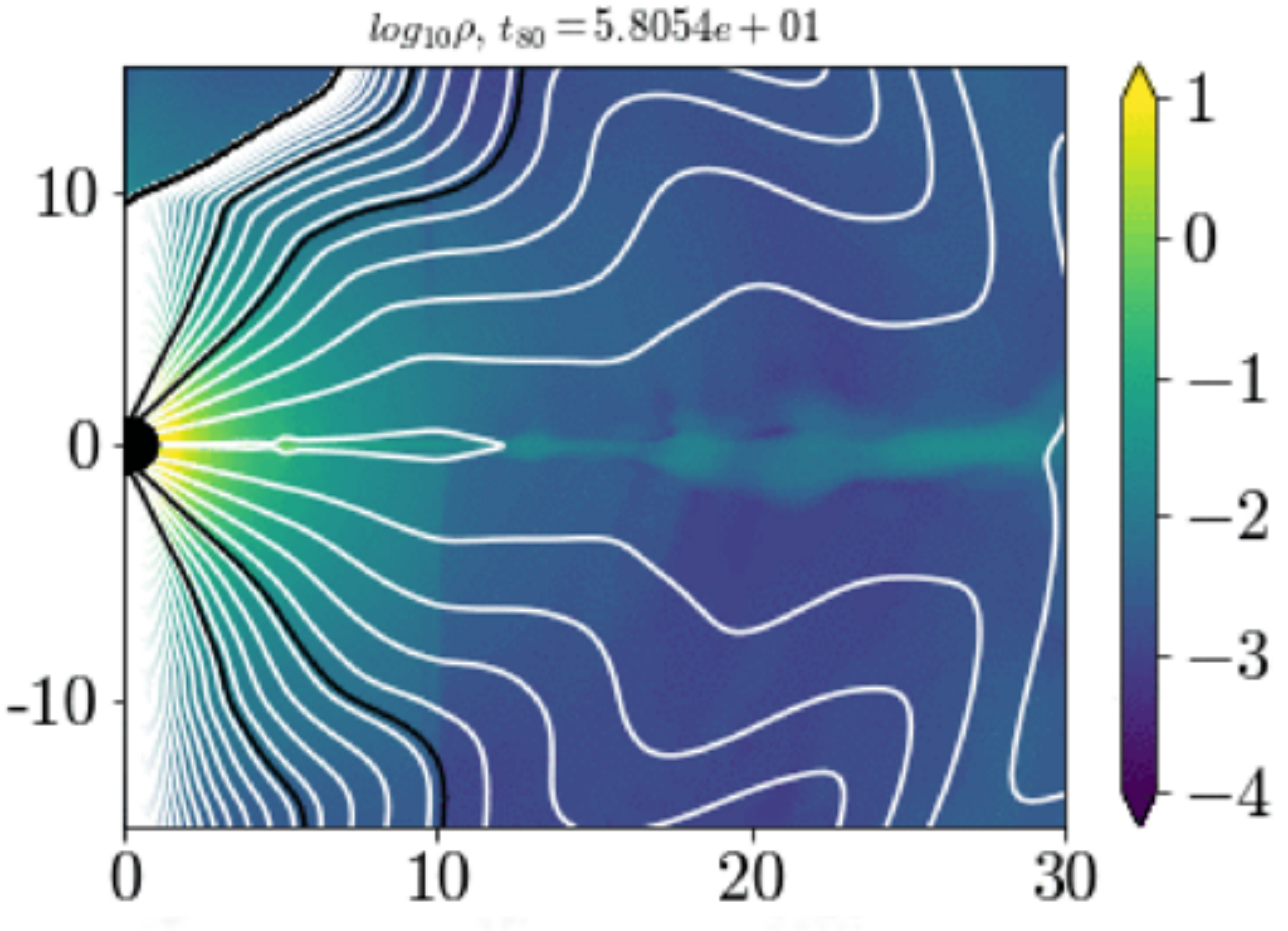
$$A_\theta = -B_x a(r\sin^2\theta + M\cos^2\theta)\cos\psi - B_x(r^2\cos^2\theta - Mr\cos 2\theta + a^2\cos 2\theta)\sin\psi, \tag{5}$$

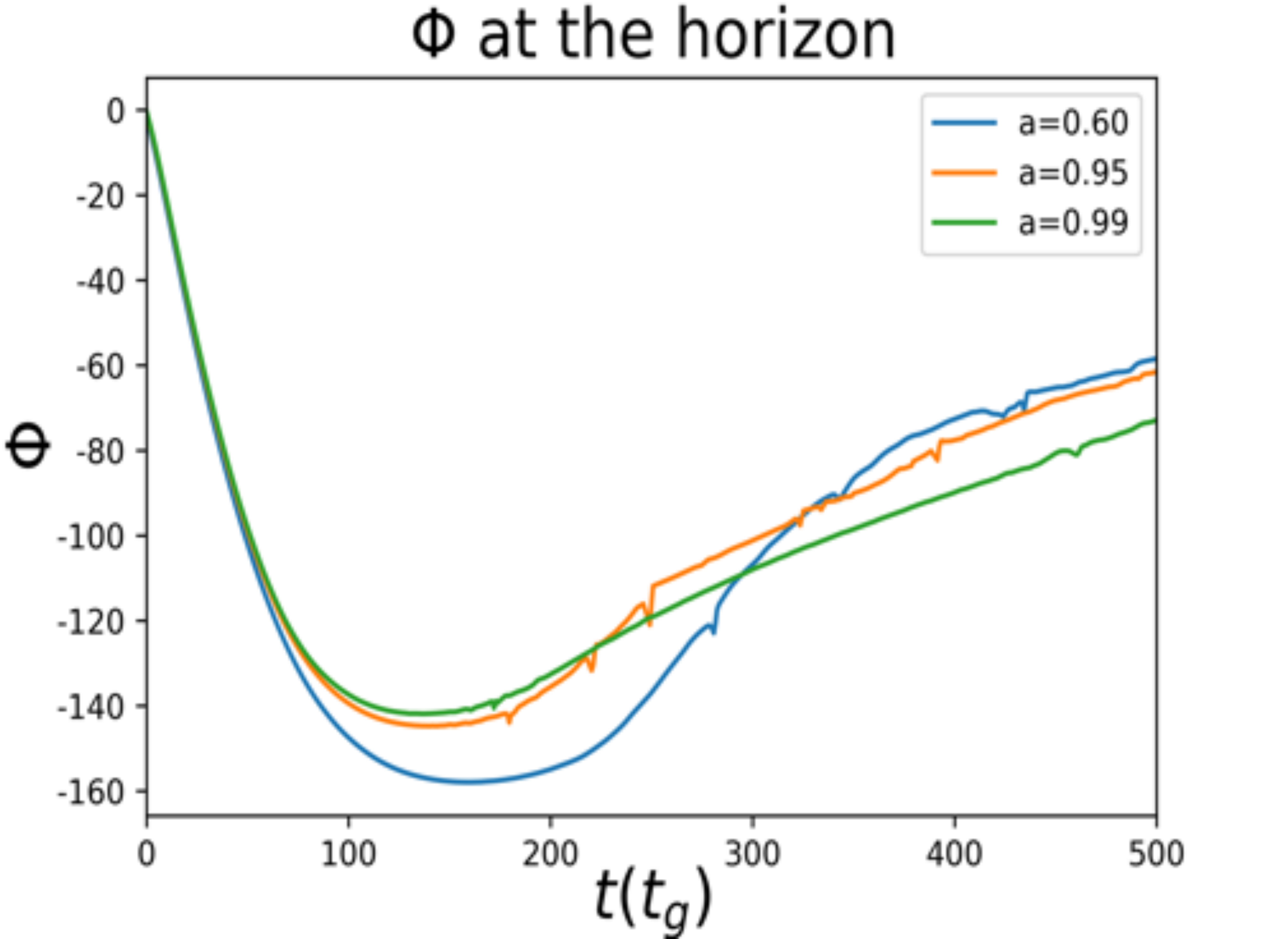
$$\begin{aligned} A_\varphi = {} & B_z\sin^2\theta\left[\frac{1}{2}(r^2+a^2) - \frac{a^2 M r}{\Sigma}(1+\cos^2\theta)\right] \\ & - B_x\sin\theta\cos\theta\left[\Delta\cos\psi + \frac{(r^2+a^2)M}{\Sigma}\left(r\cos\psi - a\sin\psi\right)\right], \end{aligned} \tag{6}$$

where ψ denotes the azimuthal coordinate of Kerr ingoing coordinates, which is expressed in Boyer–Lindquist coordinates as follows:

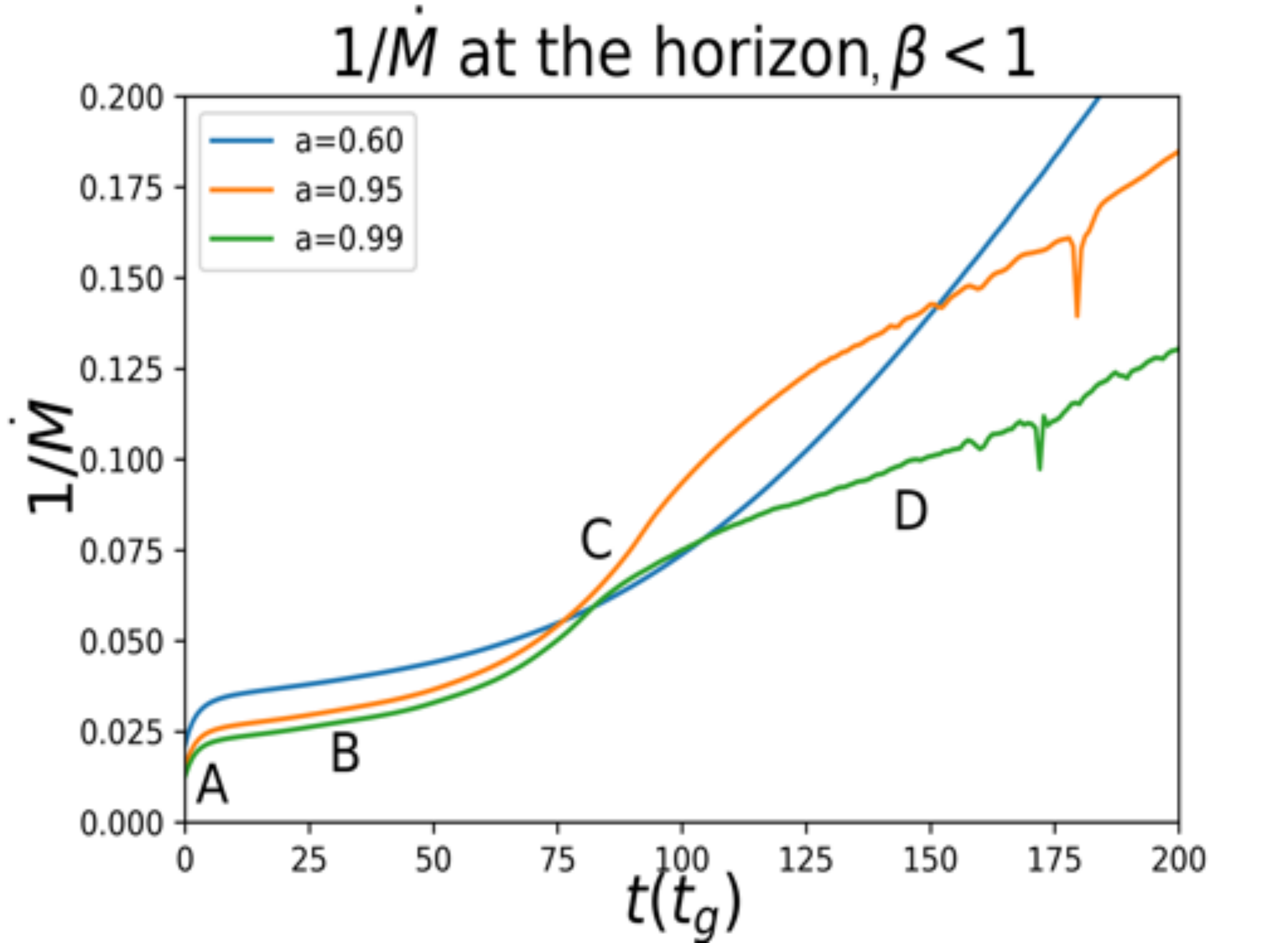
$$\psi = \varphi + \frac{a}{r_+ - r_-}\ln\frac{r-r_+}{r-r_-}. \tag{7}$$


2
1
0
-1
-2
0
2
4
1
0
−1
−2
−3


$log_{10}\rho$, $t_{80} = 5.8054e+01$
10
0
-10
0
10
20
30
1
0
−1
−2
−3
−4



Φ at the horizon
a=0.60
a=0.95
a=0.99
Φ
0
-20
-40
-60
-80
-100
-120
-140
-160
0
100
200
300
400
500
t(t_g)



1/Ṁ at the horizon, β < 1
a=0.60
a=0.95
a=0.99
A
B
C
D
0.000
0.025
0.050
0.075
0.100
0.125
0.150
0.175
0.200
0
25
50
75
100
125
150
175
200
1/Ṁ
t(t_g)

Summary

In this contribution we show an example of an equatorial outflow driven by a large scale magnetic field. We initiate our computations with an axially symmetric configuration of a uniform (Wald) magnetic field aligned with the common rotation axis of the black hole and the accretion disk. For the fluid distribution we assume a spherically symmetric (Bondi) accretion flow infalling initially onto the black hole from a large distance, $r \gg R_+$. Then we evolve the initial configuration in the force-free limit of a perfectly conducting fluid.

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.