Role of reconnection in the ejection of flux ropes and making of the flares nearby the supermassive black holes

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Work group in CAMK + Opava

Introduction-episodic jets

•In the accreting systems, large scale jets are usually steady, while episodic jets are sometimes related to flares, which are observed on the smaller scale. One example is Sgr A*, the massive BH in the Galactic center, where we observe radio, infrared and X-ray flares several times a day. Delays in peaks in the light curves at different wavebands and their fast rise and slow decay in the brightness and polarisation are probably related to the ejection and expansion of plasmoids from the accretion flow.

•Knots in jets, which could be related to episodic emission, are also observed, e.g. in 3C 120 and M87.

•Blandford & Znajek (1977) and Blandford & Payne (1982) give models for continuous jets, but we still do not have a viable model for episodic jets.

•Yuan et al. (2009) suggested a model in analogy with Coronal Mass Ejections (CMEs) in the Sun, with the closed magnetic field lines emerging from the main body of the accretion flow, expelled to the corona region: The footpoints of the magnetic loops are positioned in the turbulent accretion flow, and their twisting results in magnetic reconnection forming the flux ropes. The initial equilibrium between the magnetic magnetic pressure is disturbed by ongoing reconnection, so that the flux ropes will be accelerated outwards, forming the episodic jet. Flares, observed from such jets, are from the emission by electrons accelerated by the reconnection.

•In Shende et al. (2019) another model, in analogy with Toroidal Instability from tokamak research, was proposed- also used to model the CMEs.

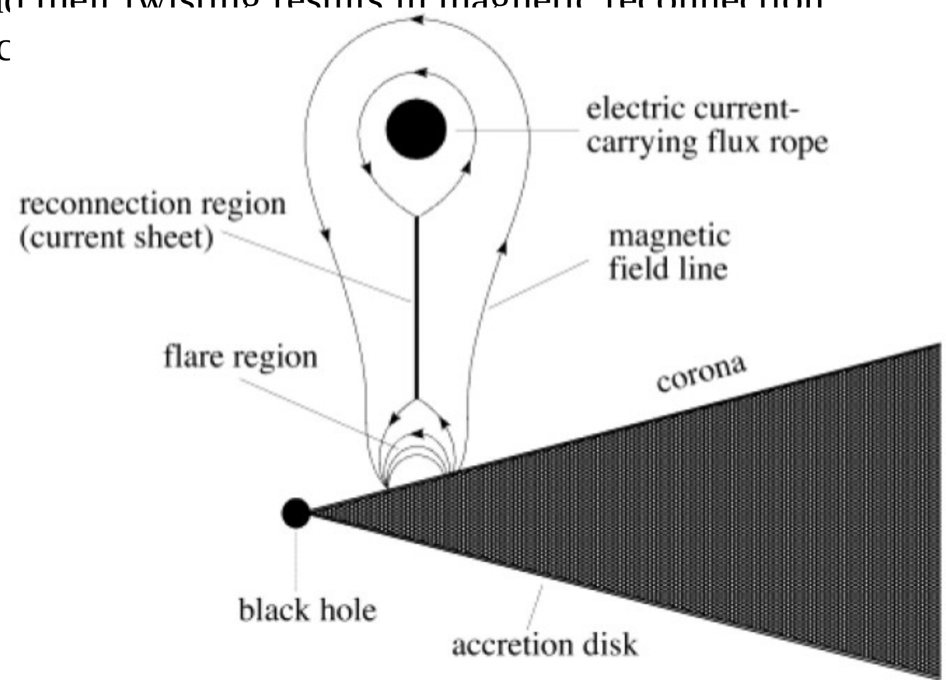


Fig. 1b from Yuan et al. (2009).

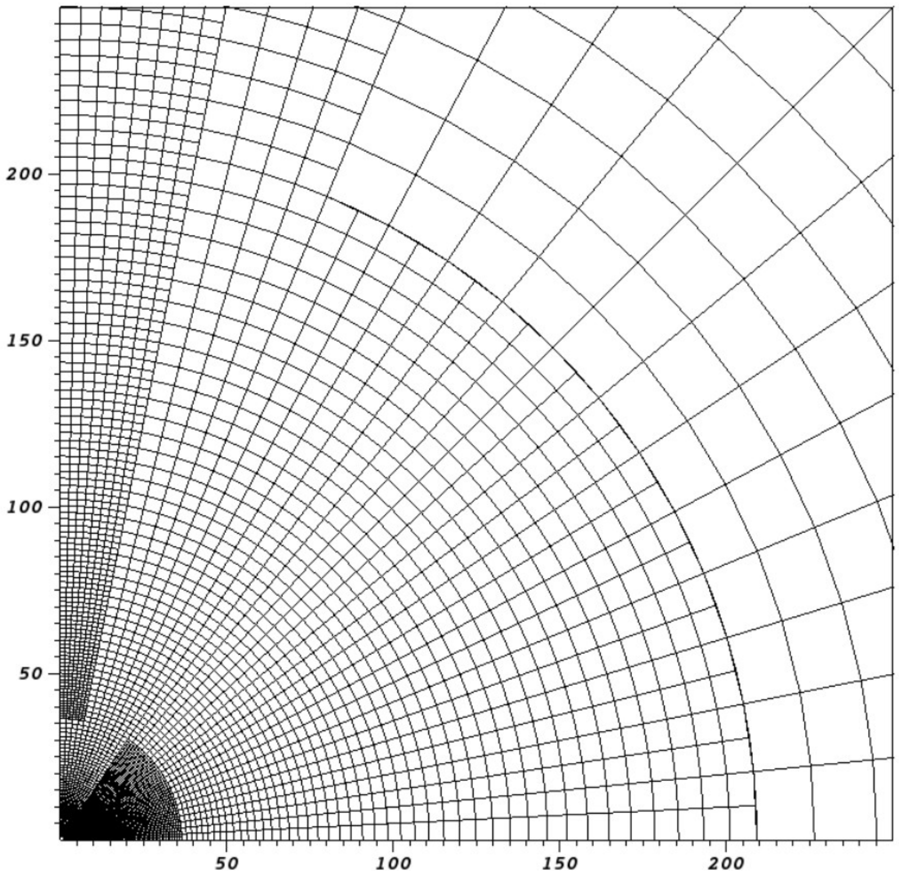
Numerical simulations setup

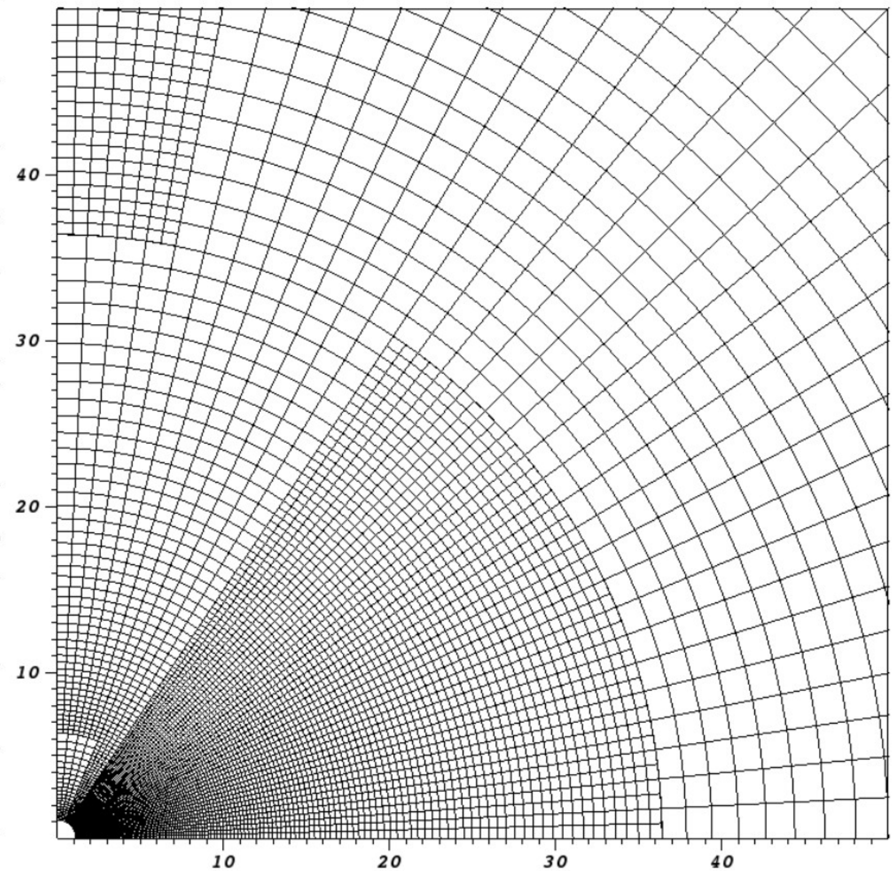
•In Cemeljic et al., Apj, 933, 55, (2022) we perform numerical simulations using the GRMHD code

Athena++ (White et al. 2016) in full 3D, solving the ideal MHD equations in the Kerr metrics, in Kerr-Schild (horizon penetrating) coordinates (t, R, θ, φ). We did both SANE (Standard and normal evolution) and MAD (Magnetically arrested disk) cases.

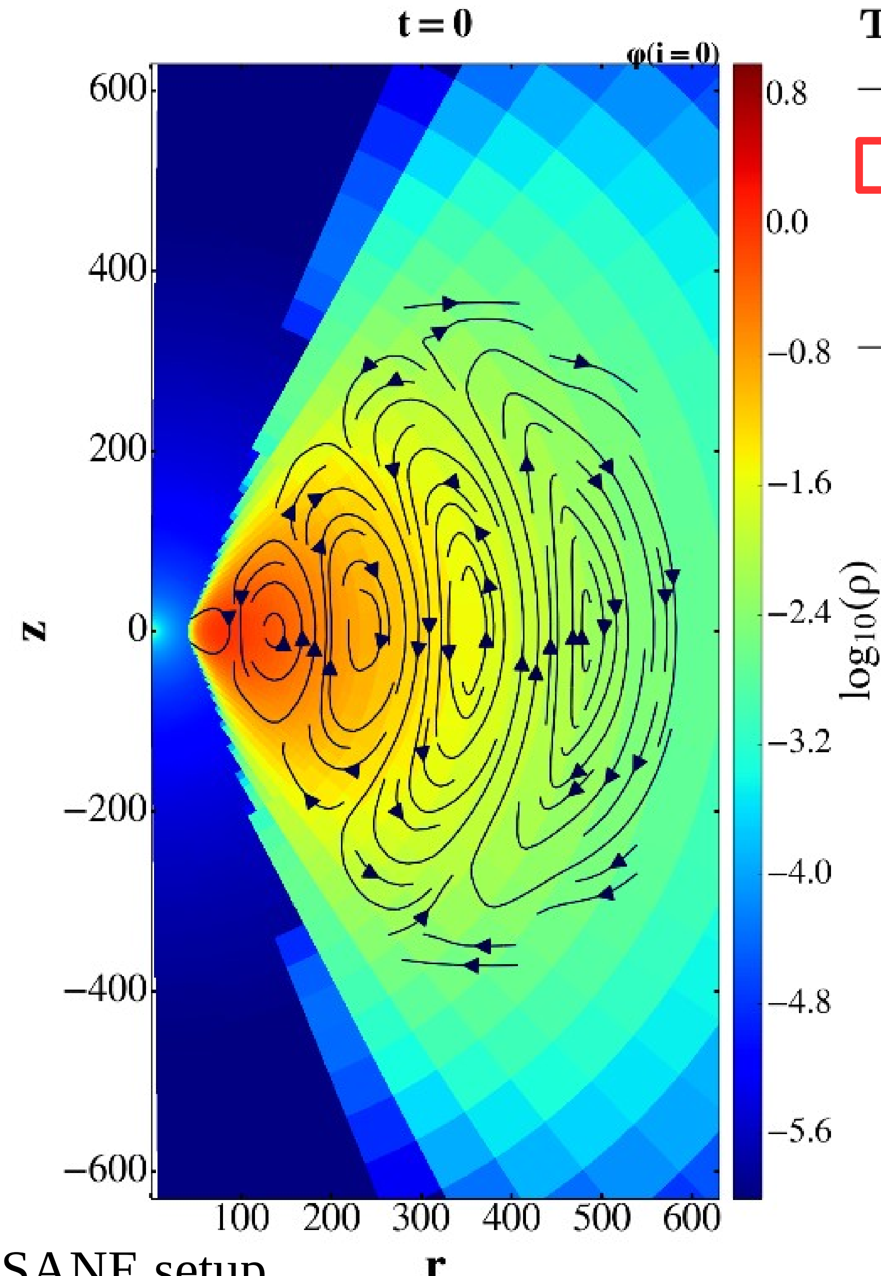
•Resolution is $R \times \vartheta \times \varphi = [704 \times 256 \times 128]$ grid cells in spherical coordinates, in a physical domain reaching to 2500 gravitational radii, with different refinements. Static mesh refinement is used to obtain largest resolution where it is most needed.

•The staggered mesh Constrained Transport method is applied to maintain the divergence-free magnetic field.





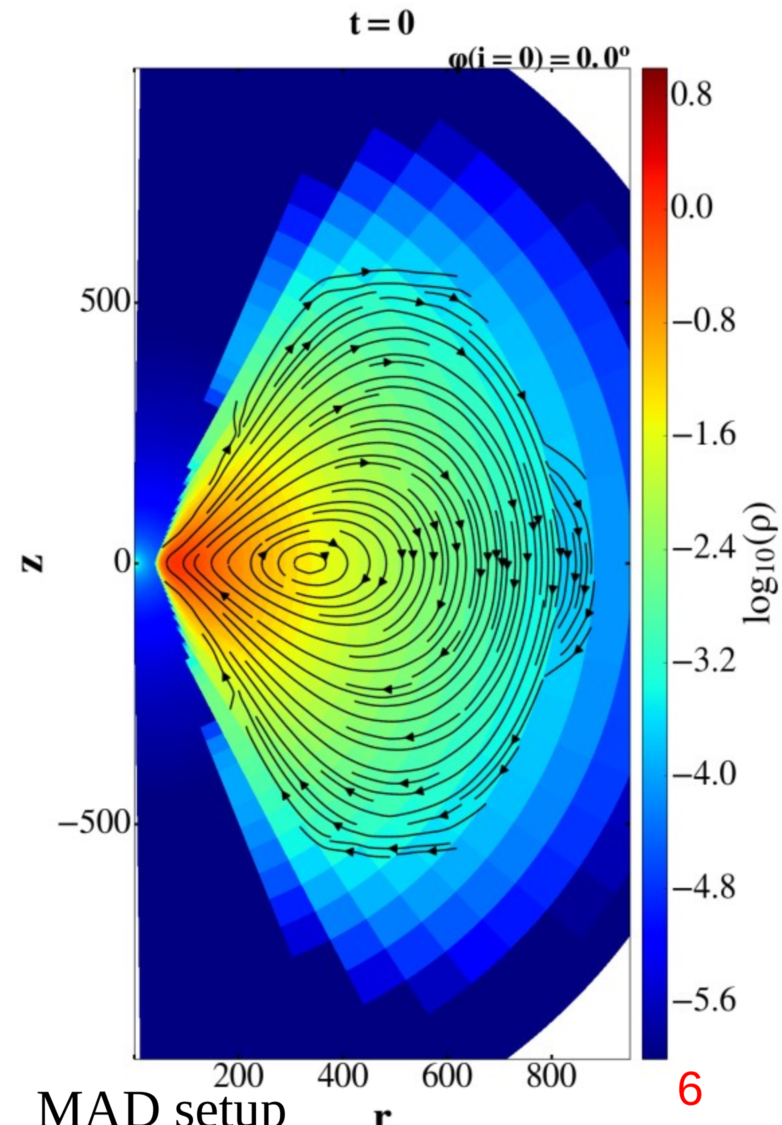
Initial conditions



SANE setup

Table 1. Parameters used in different cases in our simulations.

Model	a	β_{min}	N_r	N_θ	N_ϕ	*Duration*
SANE00	0	0.05833	288	128	64	40000
MAD00	0	0.1	288	128	64	40000
SANE98	0.98	0.03	352	128	64	40000
MAD98	0.98	0.1	352	128	64	40000



MAD setup

Fig. 1. Density in a logarithmic colour grading and a poloidal magnetic field contained inside the torus around a black hole in our SANE setup. Loops of poloidal magnetic field are shown with solid lines, with arrows showing the clockwise and counter-clockwise direction of the initial loops of magnetic field.

Results in the SANE case – motion of magnetic islands

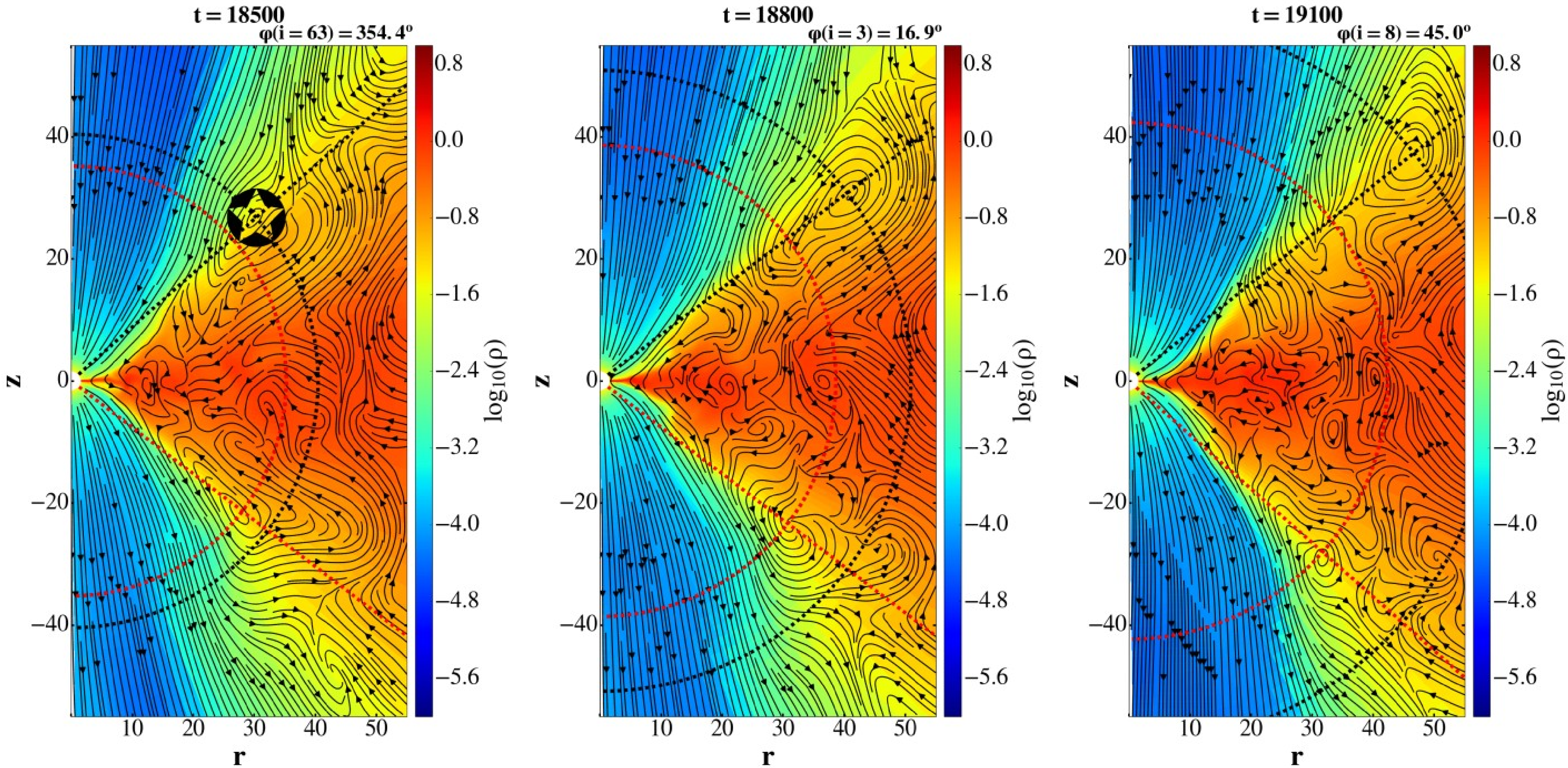


Fig 3: Slices at azimuthal planes showing density in logarithmic colour grading, overplot with poloidal magnetic field lines, computed as streamlines of poloidal magnetic field. Time is measured in r_g/c. Arrows mark the direction of the poloidal magnetic field. The dashed black and red lines are spherical coordinate lines passing through the centers of the two flux ropes. We describe the motion of the flux ropes by following the positions of their centers, which are visible as magnetic islands in the $R \times \vartheta$ poloidal plane, and analyze the velocity components, forces and other physical quantities along the dashed lines.

Motion of magnetic islands close to the BH

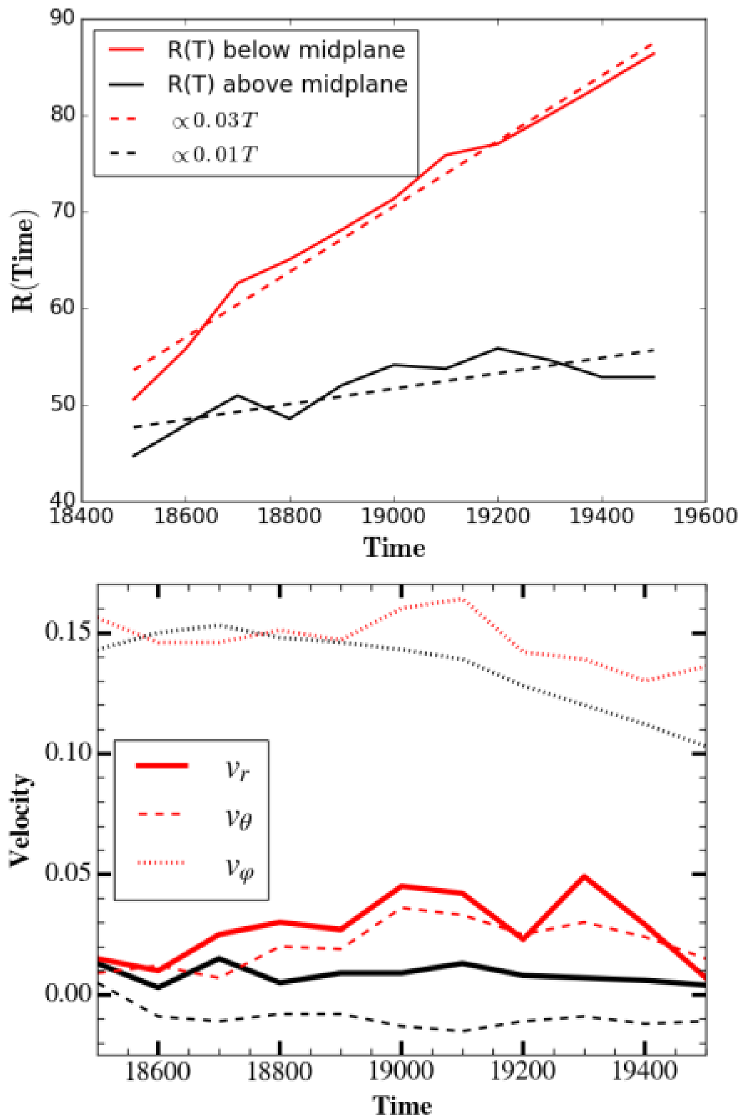


Fig. 8. *Top panel:* Time dependence of the positions of the two magnetic islands (and the flux ropes of which they are a part) above (black) and below (red) the equatorial plane of the accretion flow shown in Fig. 3. The dashed lines are the least square fits. Their slopes denote the velocity of the ropes, which are about 0.01 c and 0.03 c, respectively. *Bottom panel:* Time dependence of the components of the gas velocity near the centers of those two magnetic islands. Colors of the lines correspond to the legend in the top panel.

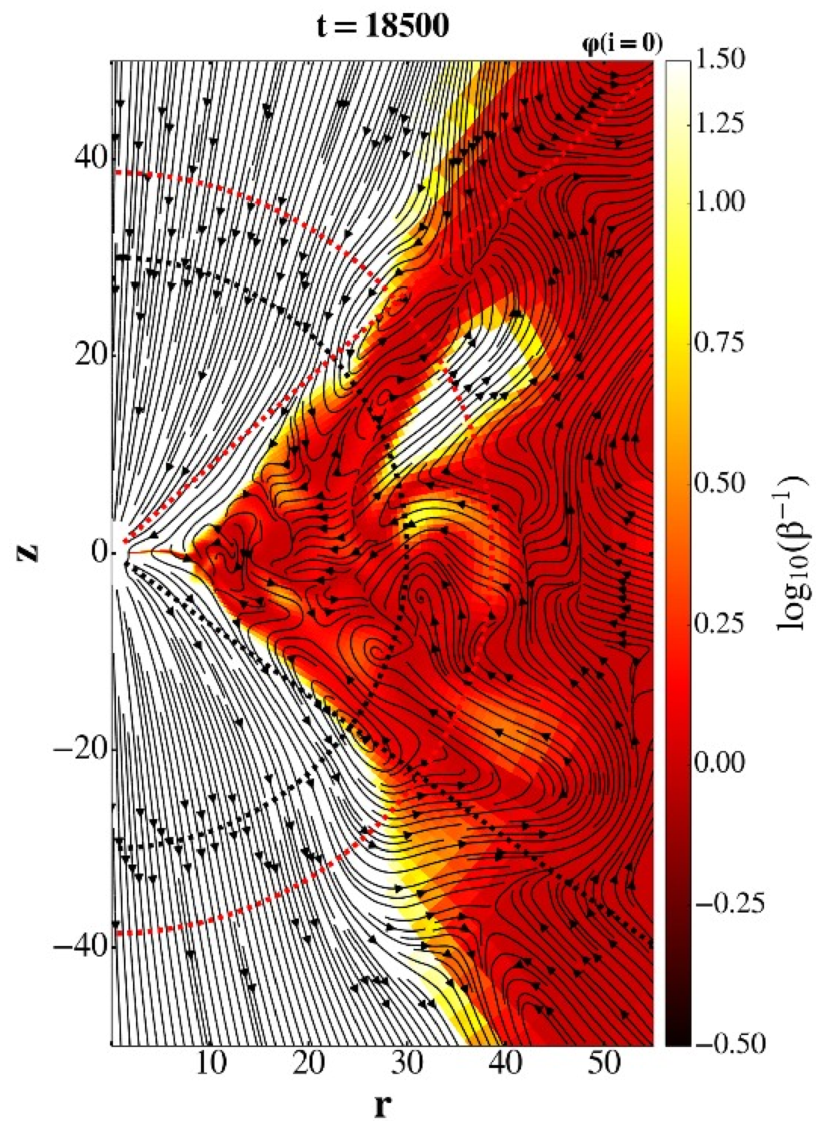
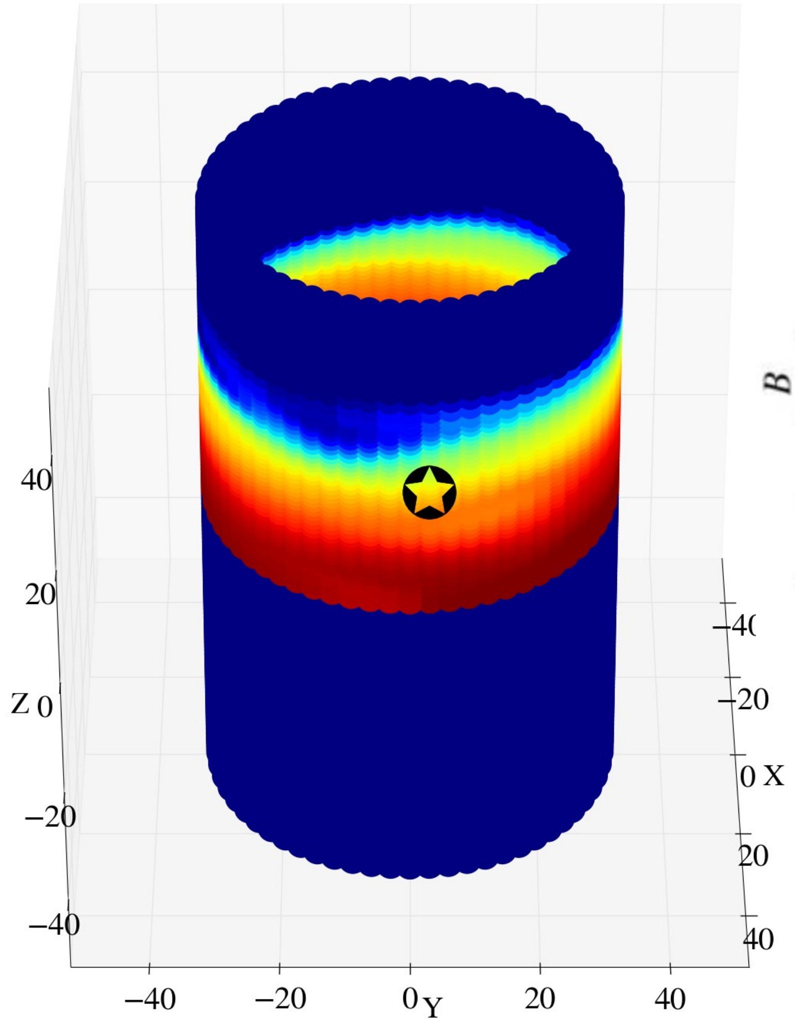
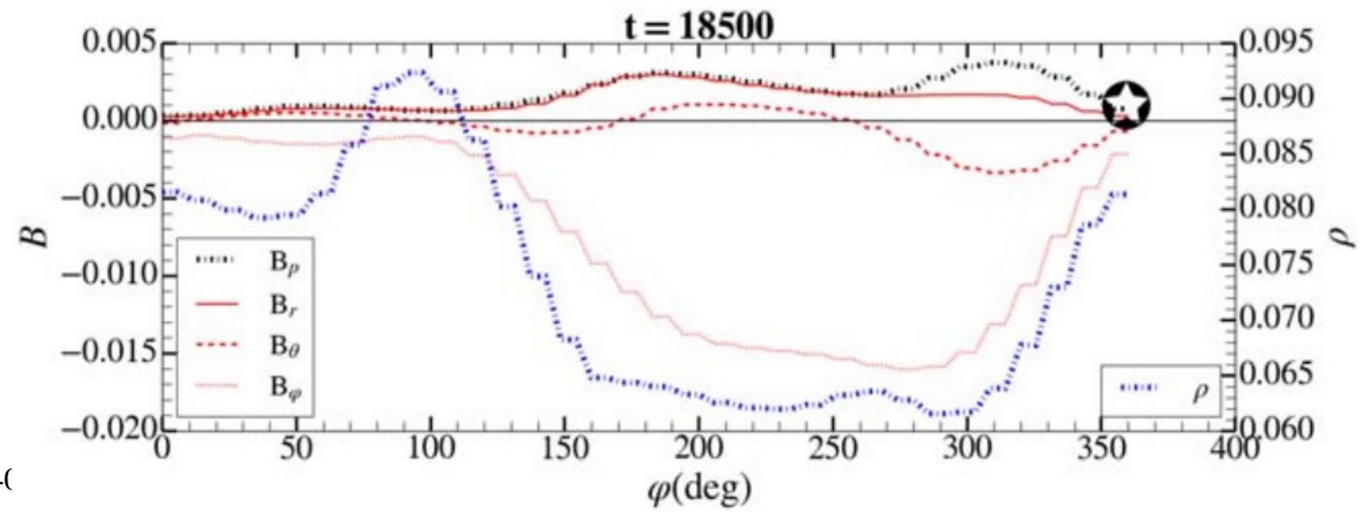


Fig. 5. Plasma β at T=18500 in our simulation shown in logarithmic color grading. Both flux ropes are positioned at the disk surface near the locations where plasma β approaches unity.

$\beta = P_{gas}/P_{mag}$

Flux rope





The flux rope and reconnection layers are positioned around the local minima of the poloidal magnetic field strength, and local maxima of the density. This is an example of a magnetic flux rope emerging from the disk surface and rotating with it.

Emerging of the magnetic flux rope from the disk surface

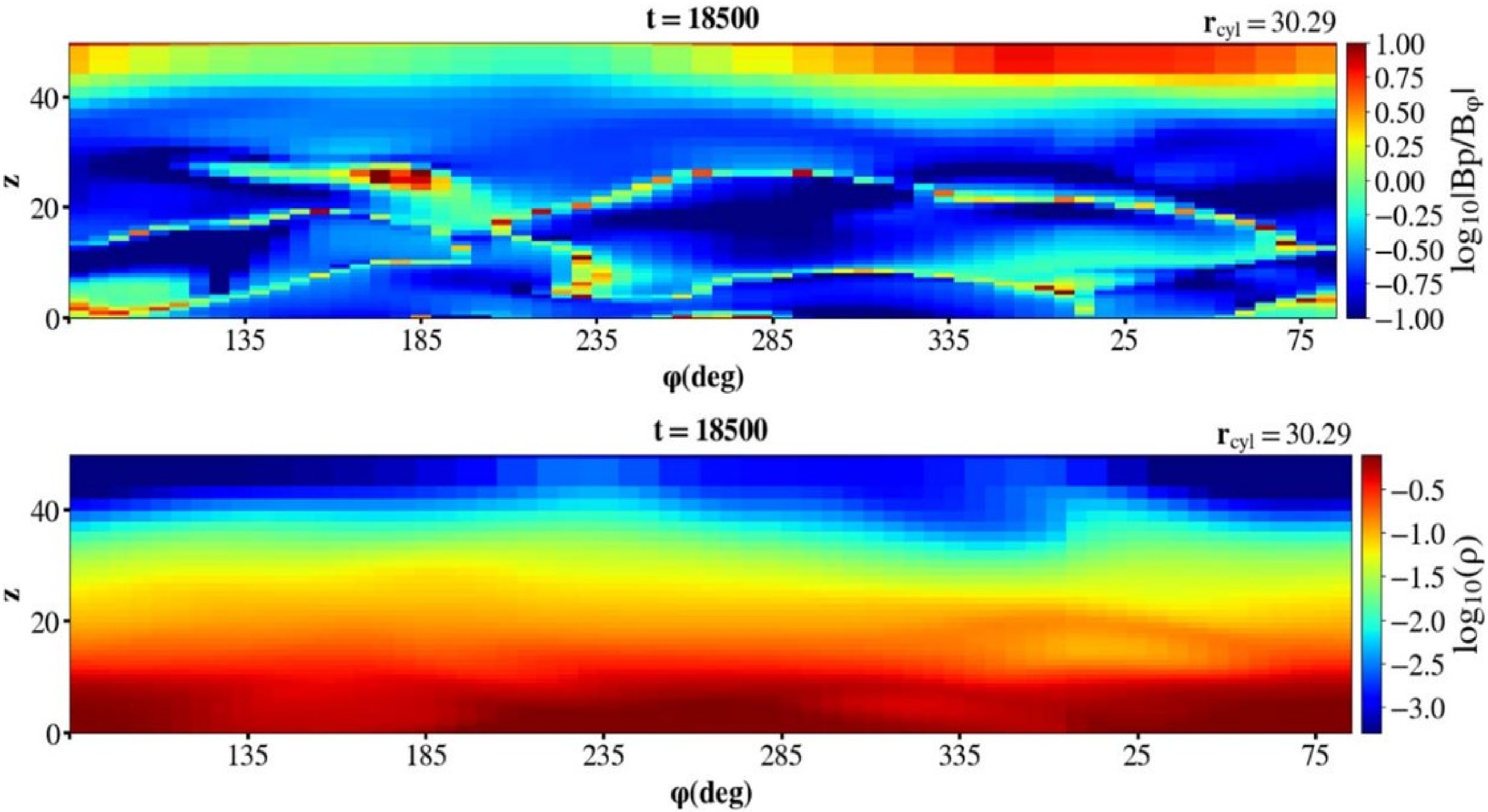
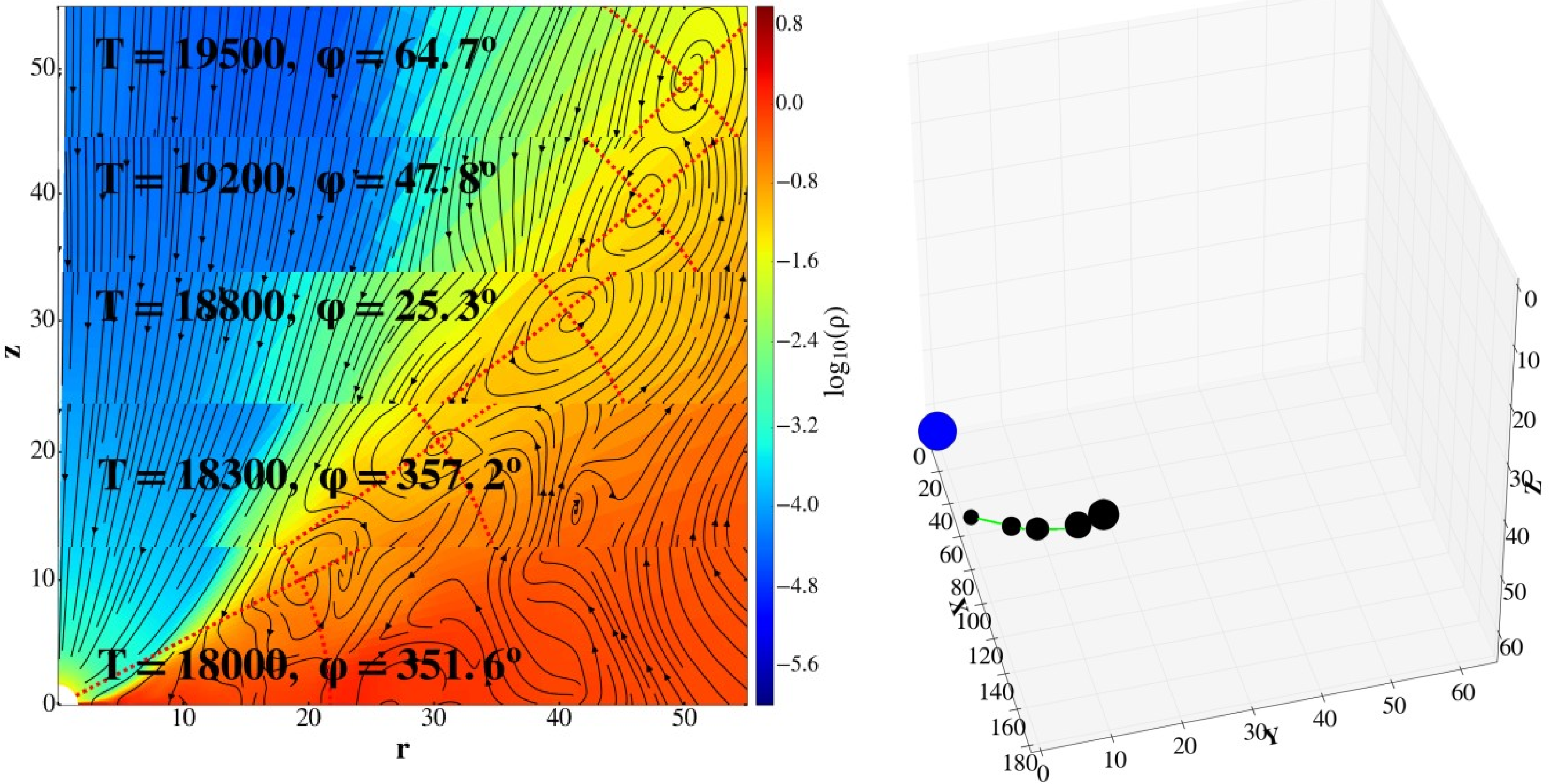


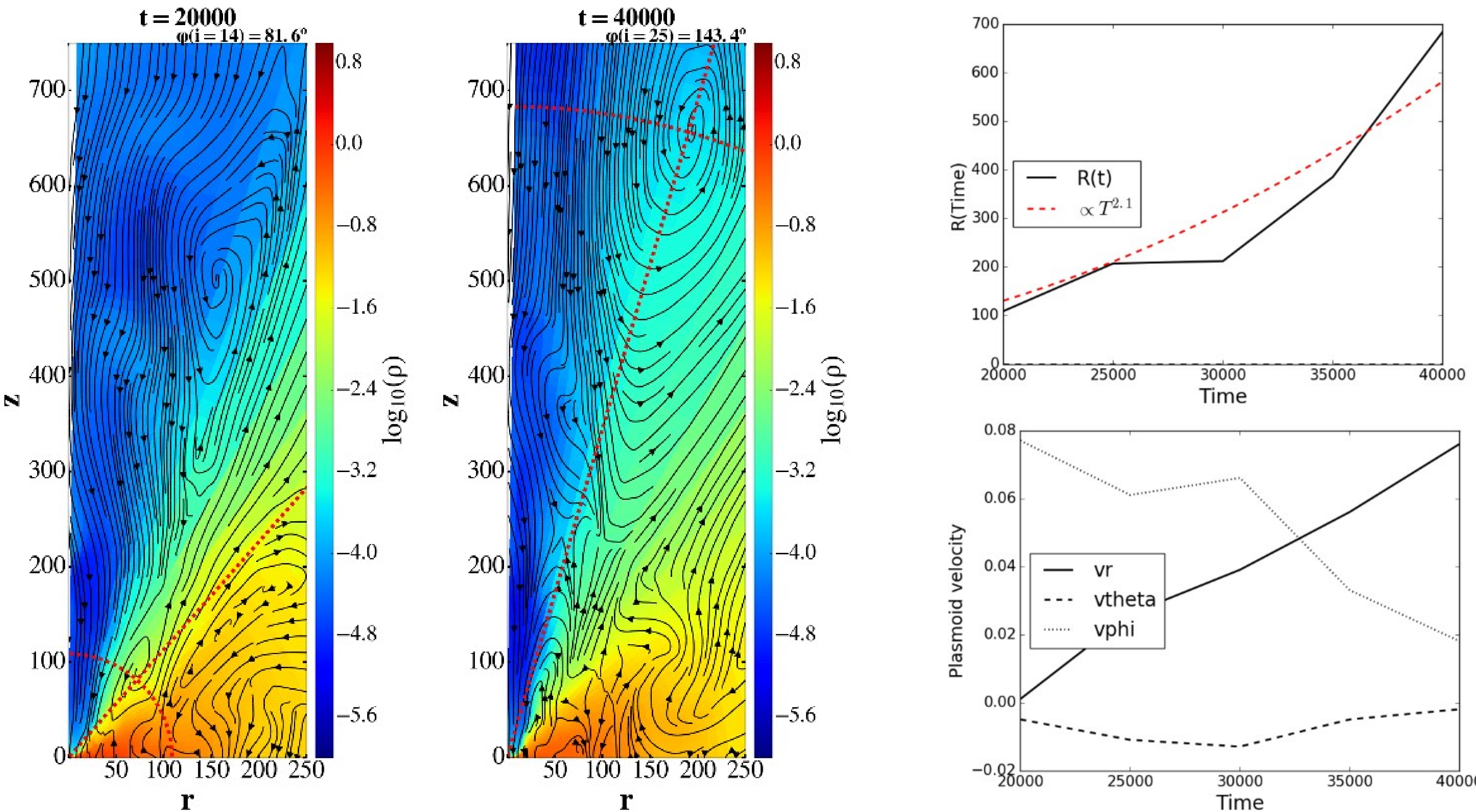
Figure 5. Spatial distribution of the magnetic field strength and density when a flux rope is present in the SANE model. Top panel: distribution of the ratio of poloidal and toroidal magnetic field strength in the $\varphi-z$ plane with a constant cylindrical radius $r = 30.29$ above the equatorial plane at $T = 18{,}500 r_g/c$. The poloidal field reaches a local minimum at the center of the flux rope, which is shown as a slice through the azimuthal extensions of the magnetic islands. Bottom panel: distribution of density in the same $\varphi-z$ plane. It is clear that the density of gas in the flux rope (the middle of which is located around $(\varphi, z) = (25°, 20)$ in this case) is higher than the surrounding medium. Note that only parts of the arcs of the flux ropes lie in this $\varphi-z$ plane because the cylindrical radius of the flux rope is not constant.

Spiraling-out of the flux ropes



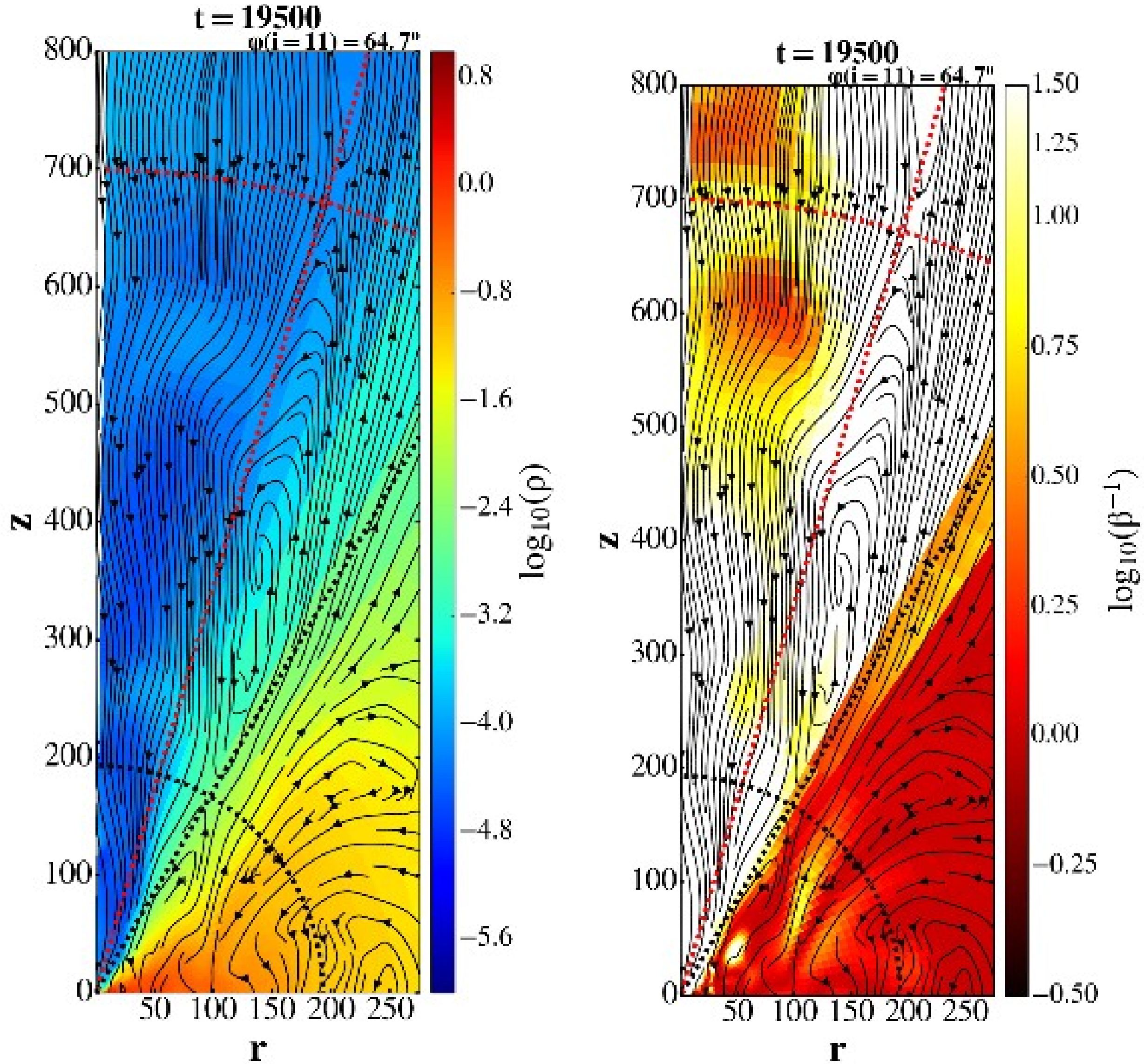
Slices at different times crossing the middle of the flux rope in our simulation (left panel). The distance from the origin is increasing in time. The angle φ of the colatitudinal plane in which the middle of the flux rope is positioned, is also increasing with time and given in the figure. The flux rope is spiraling away from the black hole, as shown in the 3D plot (right panel) depicting the trajectory of its center.

Ejection of the flux ropes



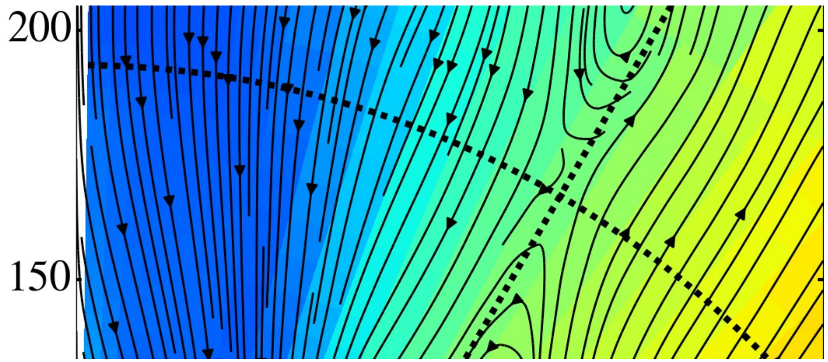
Slices at different azimuthal planes in SANE simulation at times T=20 000 and T=40 000, during the ejection of the flux rope in the corona. We describe the motion of the flux ropes by following the positions of their centers, and analyze the velocity components along the dashed lines. The velocity can reach 0.3c and 0.08c for MAD and SANE, respectively. Acceleration is also found, in both cases-from the forces we conclude that the acceleration is mainly due to the gradient of the magnetic pressure-Lorentz force is the dominant force, accelerating the flux rope.

Reconnection layers



Reconnection layers in the snapshot at T=19500 in our simulation along the disk boundary, where the flux rope emerges. In the left panel are shown the poloidal magnetic field lines with density in logarithmic colour grading as a background, and in the right panel the background is plasma β. With red and black dotted lines are shown the coordinate lines, along which we compute the physical quantities.

Reconection



A zoom into one of the reconnection layers, with dotted lines along which we compute the physical quantities.

We check for the signature of reconnection:

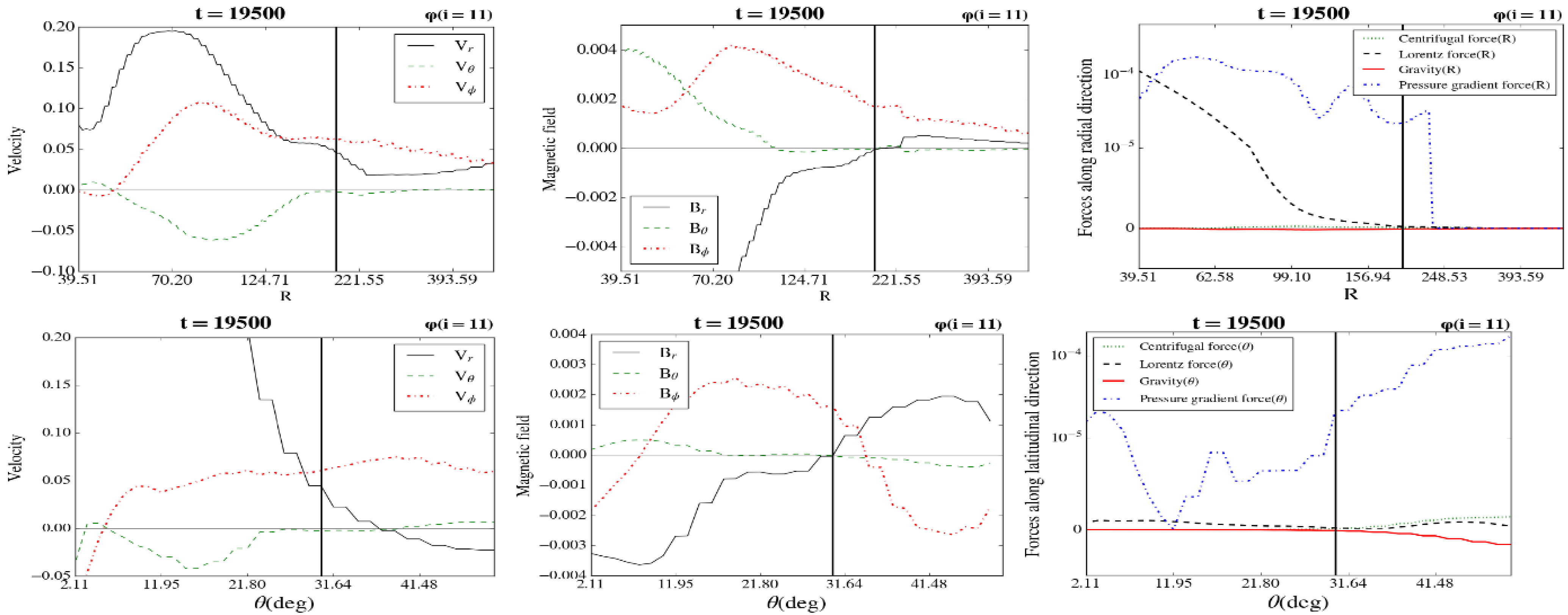
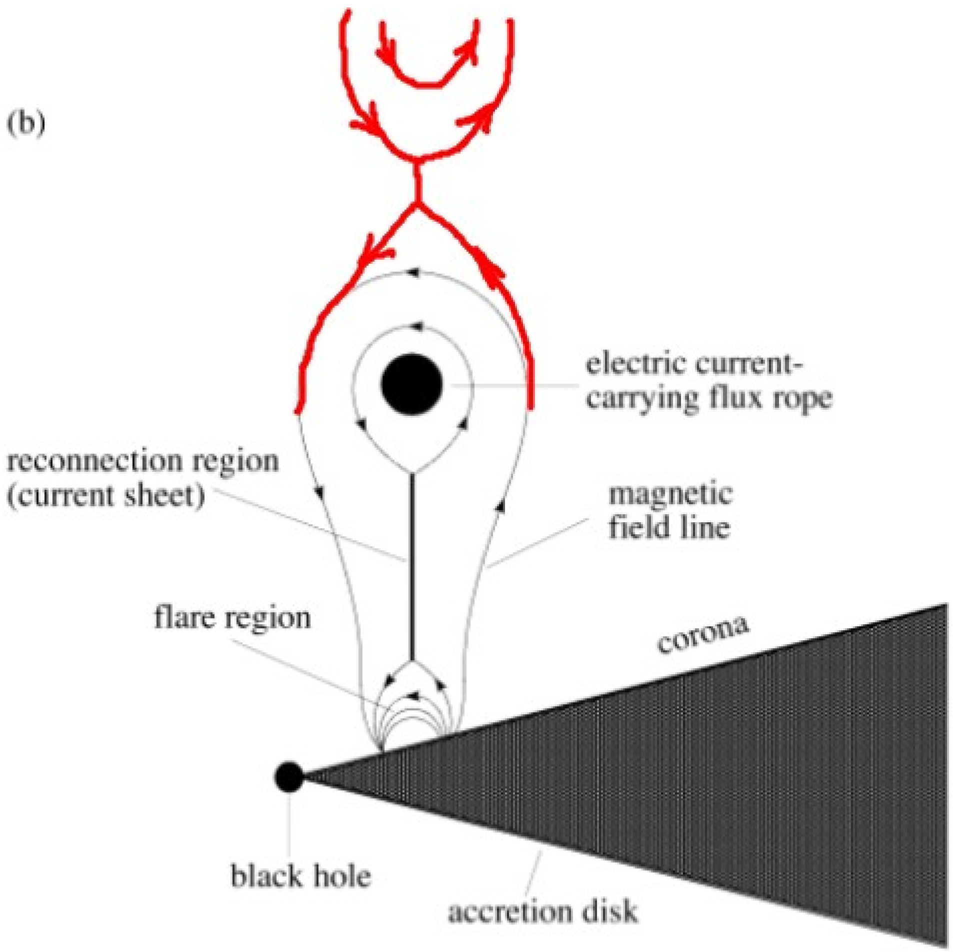


Fig. 11. Velocity, magnetic field and force components across the reconnection layer at T=19500 in our SANE00 simulation, along the coordinate lines in R and θ directions from the bottom panel in Fig. 10. In each panel a vertical solid line marks the position of the reconnection layer.

Additional reconection layer



In addition to the reconnection layer below the magnetic flux rope, there is another reconnection layer, above the magnetic flux rope in our simulations. It helps in opening of the magnetic field lines outwards from the central object.

Periodicity of the formation and ejection of flux ropes

•The flux rope formation in our simulations occurs quasi-periodically, once the simulations have reached the steady state. Period is about 1000 r_g/c, which is close to the orbiting timescale of both SANE and MAD at 20–30 r_g.

•When a plasmoid moves outwards, it may catch up and merge with a previously produced plasmoid having a slower speed. The merger of two magnetized islands must be accompanied by magnetic reconnection. This will result in electron acceleration and subsequent strong synchrotron radiation in various wave bands ranging from IR to X-ray and γ-ray in black hole sources, so strong flares are expected to occur. Yuan & Zhang (2012) proposed this scenario as the mechanism of gamma-ray bursts.

•From the over 2 hr long infrared light curve of Sgr A* , several periods of variability are identified by observations, with periods ranging from 17 to 40 minutes (Genzel et al. 2003; Eckart et al. 2006a; Trippe et al. 2007; Genzel et al. 2010). The observed periods are consistent with the orbital period at 3–5 r_g for the 3.6×10^6 solar masses black hole in Sgr A*, assuming the accretion flow in Sgr A* is a case of MAD. The typical lifetime of a hot spot is shorter than one orbit timescale, so that the detected periodicity is best explained by the periodic occurrence of reconnection events at small radii, seen in our simulation. Since the reconnection occurs in a range of radii, the observed period is not fixed, but has a range of values.

Polarization of the flares

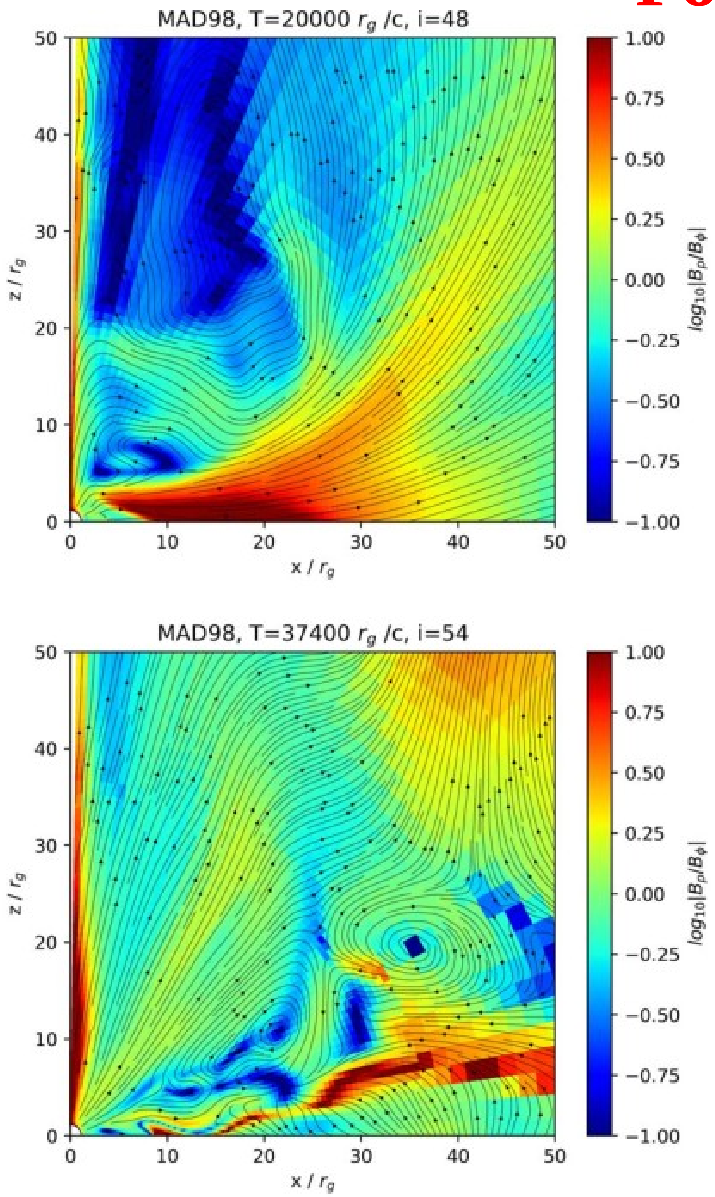


Figure 12. Properties of the magnetic field at two different evolution times. The time (T) and number of grids in the φ-direction (i) are shown at the top of each panel. The magnetic field is denoted by black solid lines with arrows indicating the direction of the field. The colors indicate the logarithmic value of the ratio of poloidal and toroidal magnetic field strength. In the top panel, two flux ropes are located at $(x, z) = (8, 7)$ and $(20, 28)$; in the bottom panel, two flux ropes are located at $(21, 12)$ and $(35, 20)$. The magnetic field in the region where the two flux ropes are located is poloidally and toroidally dominated in the top and bottom panels, respectively. At the very center of the two flux ropes in the bottom panel, the poloidal field is weaker than the toroidal field because of the occurrence of reconnection (see text for details). The figure is plotted based on the simulation data of MAD.

•From the results in Gravity Collaboration et al. (2018), we know that the flares are polarized because of the orbital motion of a hot spot in a strong poloidal magnetic field.

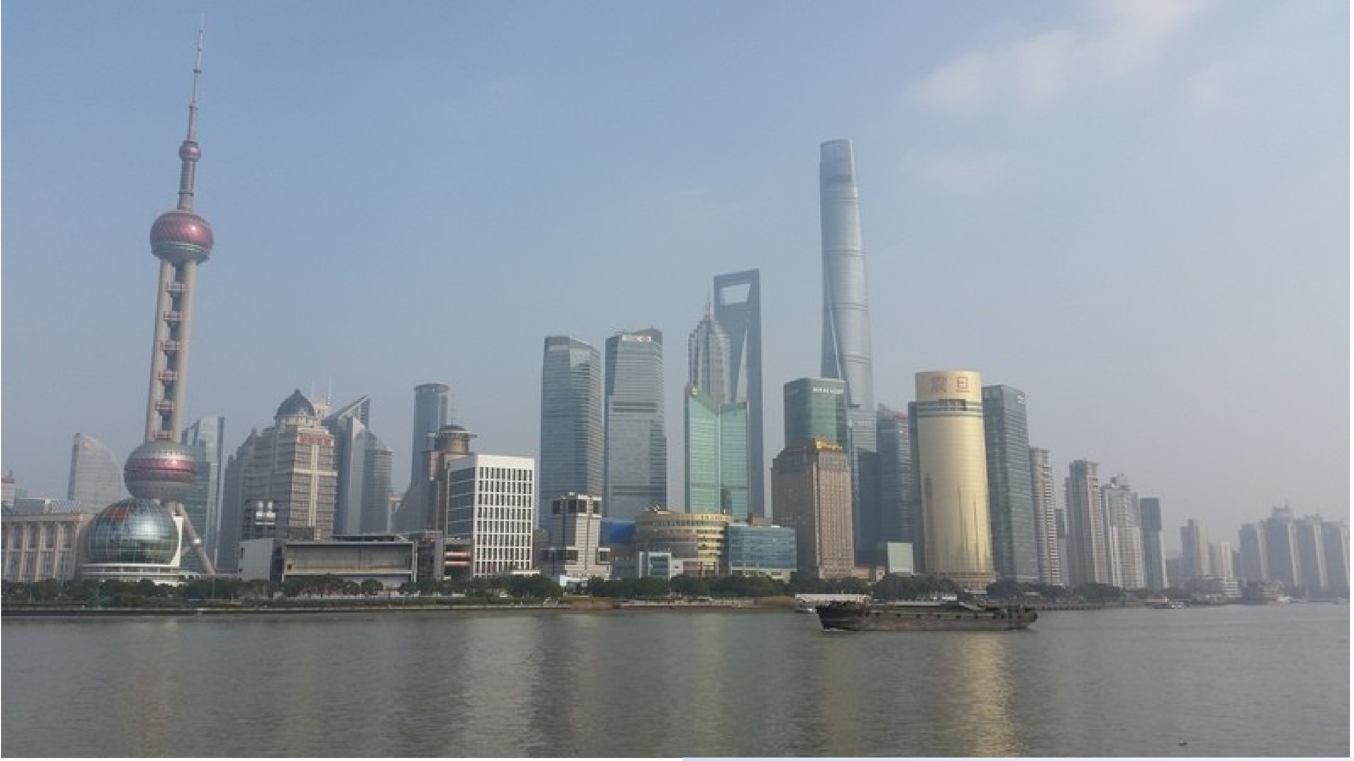
•In our simulation, we find that at the site of reconnection (i.e., the place of the hot spot), which is also roughly where the flux rope is located, the magnetic field could be dominated by either poloidal or toroidal components, depending on time. **The top panel** shows a case where the field is dominated by the *poloidal* component, which is consistent with the observation.

• At another time, shown in **the bottom panel** of this figure, the field is dominated by a *toroidal* component. This prediction could be verified by future observations.

•The detailed modeling of the IR and X-ray light curves of Sgr A* shows that magnetic field strength should decrease during the flare, for the simultaneous and symmetric X-ray and near-infrared light curves. In our simulations we find the required weakening of the magnetic field during reconnection.

Summary

- I presented our recent work, Cemeljic et al., Apj, 933, 55, (2022), on formation of magnetic flux ropes in 3D GRMHD numerical simulations with the code Athena++.
- Magnetic structures which show as magnetic islands in 2D simulations, can develop into the magnetic flux ropes in 3D.
- Flux ropes rotate and loop around the central object.
- Because of reconnection, flux ropes which form far enough of the BH to escape its strong gravity, are pushed out of the disk surface, and are launched into the corona. Additional reconnection layer can form, helping the launch of the rope. This would cause episodic flaring from the vicinity of the disk around a black hole.
- Periodicity of flux ropes formation and ejection is the orbiting time at the radius where the flux ropes are formed. This implies that differential rotation of the accretion flow plays a more important role than turbulence in twisting the magnetic field lines, and results in the formation of reconnection. Polarization and local decrease of the magnetic field is also matching the expected ones in the flares.



Thank you!