The Predictive Power of Computational Astrophysics as a Discovery Tool
Proceedings IAU Symposium No. 362, 2023
D. Bisikalo, D. Wiebe & C. Boily, eds.
doi:10.1017/S1743921322001715

Hybrid magnetic structures around spinning black holes connected to a surrounding accretion disk

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Abstract. The hot accretion flow around Kerr black holes is strongly magnetized. Magnetic field loops sustained by a surrounding accretion disk can close within the event horizon. We performed particle-in-cell simulations in Kerr metric to capture the dynamics of the electromagnetic field and of the ambient collisionless plasma in this coupled configuration. We find that a hybrid magnetic topology develops with a closed magnetosphere co-existing with open field lines threading the horizon reminiscent of the Blandford-Znajek solution. Further in the disk, highly inclined open magnetic field lines can launch a magnetically-driven wind. While the plasma is essentially force-free, a current sheet forms above the disk where magnetic reconnection produces macroscopic plasmoids and accelerates particles up to relativistic Lorentz factors. A highly dynamic Y-point forms on the furthest closed magnetic field line, with episodic reconnection events responsible for transient synchrotron emission and coronal heating.

Keywords. acceleration of particles - magnetic reconnection - black hole physics - radiation mechanisms: non-thermal - methods: numerical

1. Introduction

Accretion and ejection have been found to be tightly linked around supermassive and stellar-mass black holes (BHs). Non-thermal flares from these systems are thought to be due to particles accelerated at relativistic speeds by shocks and/or magnetic reconnection. These particles then radiate through different leptonic (and, to a lesser extent, hadronic) emission/scattering processes like synchrotron and inverse Compton emission. The origin, properties and location of the particle acceleration sites around accreting BHs remain elusive. Multiple evidence indicate that a hot and collisionless corona surrounds accreting BHs (Cangemi et al. 2021). This environment is highly magnetized and threaded by large scale poloidal magnetic field lines (The Event Horizon Telescope collaboration 2021a). This highly ordered magnetic field is sustained by an accretion disk whose dynamics is well represented by the idealized magneto-hydrodynamics framework (The Event Horizon Telescope collaboration 2021b). In contrast, the corona is essentially force free. Last physical ingredient but not least, these BHs have jets which are thought to be rotation-driven. In the high-mass X-ray binary Cygnus X-1, some diagnostiscs based on thermal continuum fitting or X-ray reflection spectroscopy suggest that the stellar-mass BH might be maximally spinning (Miller-Jones et al. 2021). Things are less clear for the supermassive BHs Sagittarius A* (SgrA*) and M87* but the joint efforts of the Gravity and EHT collaborations could bear fruits in the years to come.

I first describe the model we rely on. Then, I present the results we obtained in terms of topology of the magnetic field in the corona and of particle acceleration driven by magnetic reconnection in the corona.

2. Model

2.1. *Kerr black hole magnetosphere*

We work on a stationary and axisymmetric Kerr spacetime produced by a rotating BH with mass M and dimensionless spin a. The problem is scale-invariant with the gravitational radius $r_g = GM/c^2$ as length scale (with c the speed of light and G the gravitational constant. We use the 3+1 formalism and Kerr-Schild spherical coordinates to alleviate the coordinate singularity which arises at the event horizon in other coordinate systems. We focus on the corona. The disk itself is not modeled in our particle-in-cell (PIC) simulations. Instead, it serves as a background steady environment where magnetic field lines are frozen and co-rotate with their footpoint on the disk. The angular speed profile in the disk is assumed to be Keplerian. We inject electron/positron pairs in the corona in a ad hoc manner such as (i) the charge density is high enough for the force-free regime to be possible, (ii) the magnetization remains $\gg 1$ and (iii) the plasma skin depth is resolved.

Since the seminal work by Blandford & Znajek in the 70's, most models of rotating BH magnetospheres focused on a specific configuration where magnetic field lines passing through the BH are open, a particularly convenient framework to launch jets and outflows. In contrast, fewer studies considered the alternative case: a Kerr BH surrounded by a geometrically thin accretion disk threaded by a large scale magnetic field connected to the BH. This coupling configuration has been studied by Uzdensky (2005) and more recently by Yuan et al. (2019) but they worked in the purely force-free approximation which cannot capture dissipative effects or changes of the topology of the magnetic field.

2.2. *Numerical setup*

We work on a 2D grid with axisymmetry around the BH spin axis. The disk is located in the equatorial plane of the BH and we only consider the part of the corona above the disk. The inner boundary is located within the event horizon to prevent any numerical artifact which might appear due to the boundary conditions to propagate upstream. The outer boundary is located at 30 r_g, with a region between 27 and 30 r_g where particles are deleted and the electromagnetic fields are damped. The resolution of the grid is 2,048 radial cells and 1,120 azimuthal cells. The resolution of the grid is high enough to capture the kinetic scales associated to the electron/positron pair plasma. The plasma injection method we use typically results in the simulation space being filled with a few 10^8 particles.

We use the fully relativistic `GRZeltron` code first introduced by Parfrey et al. (2019) and based on the `Zeltron` code (Cerutti et al. 2013). These PIC simulations rely on a hybrid Eulerian/Lagrangian approach (see Figure 1): electromagnetic fields on a grid are advanced in time by numerically solving Maxwell-Faraday and Maxwell-Ampère equations while charged particles move on this grid under the influence of the Lorentz force produced by the electromagnetic fields and of other user-defined forces. The plasma is collisionless in the sense that particles do not directly interact with each other but collective plasma effects can arise owing to the interplay with the electromagnetic fields. In `GRZeltron`, after particles were pushed, charges and currents are deposited on the grid following a first-order scheme. The lack of conservativity of this method is compensated by the resort to a divergence cleaning step based on an iterative Gauss-Seidel relaxation scheme such that Maxwell-Gauss equation is verified (Cerutti et al. 2015). `GRZeltron`

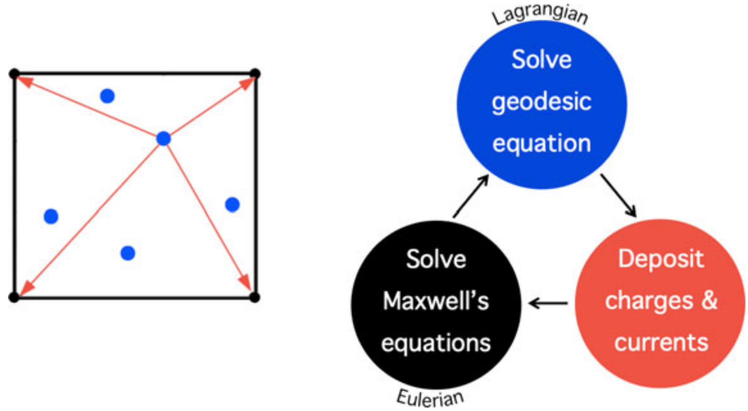

Figure 1. Principle of a PIC code, with the three main steps: (i) advancing the magnetic and electric fields on a grid by solving Maxwell-Faraday and Maxwell-Ampère equations respectively (in black), (ii) solving the equation of motion for particles (in blue) and (iii) depositing the charges and currents on the nodes of the grid to be used as source terms for Maxwell equations (in red).

uses a staggered grid which guarantees that an initially divergence-free magnetic field remains so to machine precision as the field evolves in time (Yee 1966).

In the initial state, the plasma is permeated with a poloidal magnetic field which threads the horizon and is anchored at its other end into a steady, geometrically thin, aligned and perfectly conducting disk in Keplerian rotation. The disk extends all the way down the innermost stable circular orbit (ISCO). In what follows, we explore the influence of the BH spin for $a \geq 0.6$ but we also ran simulations with $a = -0.8$ (counter-rotating disk) and for a slim accretion disk that we do not discuss in detail here. For complementary information, see El Mellah et al. (2021).

3. Results

3.1. *Hybrid magnetosphere*

First of all, let us inspect the structure of the magnetic field. As the initial condition relaxes, we observe a phenomena first highlighted by Uzdensky (2005). If the BH spins, magnetic field lines are sheared because in the ergosphere, they are dragged by the Lense-Thirring effect and rotate at a different speed from the one of their foot-point on the disk. Accordingly, we observe the following relaxation of the magnetic field from the initial state: a toroidal component grows, propagates outward and leads to the opening of magnetic field lines beyond a certain critical distance. It is the general relativistic analogue of the magnetic field lines around a spinning neutron star which open beyond the light cylinder. The main difference here is that a disk is needed since the BH cannot sustain its own magnetic field. In the left panel Figure 2, we represent the 3D topology of the magnetic field lines by assuming axisymmetry around the BH spin axis. The open magnetic field lines are either anchored in the disk or threading the event horizon. The latter are strongly twisted and will form the backbone of an electromagnetic jet à-la Blandford-Znajek (Blandford and Znajek 1977). The former are inclined enough to launch a magneto-centrifugal wind according to the Blandford-Payne criteria (Blandford and Payne 1982). In-between the two, the shearing is low enough that magnetic field lines coupling the disk to the BH remain and form a closed magnetosphere (see the two innermost magnetic field lines in the left panel in Figure 2). The smaller

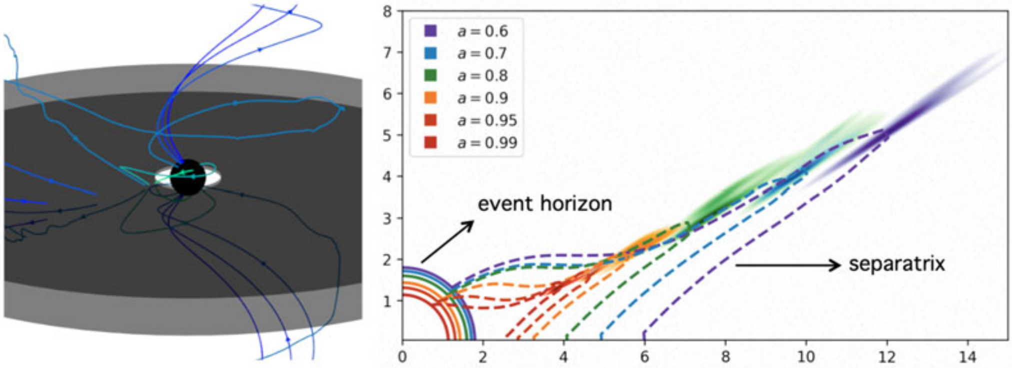

Figure 2. (Left) 3D representation of the magnetic field lines above and below the disk (black semi-transparent wedges). The central black sphere stands for the BH event horizon. (Right) Separatrix for different BH spins (dashed lines). Color-shaded regions stand for the probability map of the Y-point location. The x and y-axis are in units of the gravitational radius r_g.

the BH spin, the more extended the outermost closed magnetic field line (hereafter, the separatrix), as visible in the right panel in Figure 2.

We computed the jet power as the Poynting flux in the region of the open magnetic field lines threading the horizon. Provided we account for the correcting factor derived by Tchekhovskoy et al. (2011) at high spin, we obtain a dependence of the jet power on the spin which is fully in agreement with the force-free formula. It is consistent with the uniform angular speed of the open magnetic field lines threading the horizon which matches half of the BH angular speed. Through the coupling magnetic field lines, energy and angular momentum are transported from the BH to the disk (for $a \geq 0.6$). Energy is deposited at a rate of the order of 10% of the jet power and for high spin values, we compute angular momentum transfer rates high enough to modify the structure of the disk within an accretion time scale. Here again, the values we measure correspond to the force-free predictions.

3.2. *Particle acceleration*

At the intersection of the 3 aforementioned regions, a Y-point forms at the furthest point on the separatrix. From this point, a current sheet develops where magnetic reconnection happens and plasmoids form (see Figure 3). In this highly non force-free region, electromagnetic energy is converted into particle kinetic energy. Particle acceleration is more efficient for higher spin, with maximum Lorentz factors of the order of a few 100 for $a = 0.99$. Most of the dissipation occurs near the Y-point. The separatrix progressively stretches until a plasmoid detaches, the Y-point suddenly recedes and the cylce repeats, with a period ranging from 17 to $6r_g/c$ for a spin going from 0.6 to 0.99. The color-shaded regions in the right panel in Figure 2 correspond to the occurrence of the location of the Y-point at different times and for different spin values. This mechanism provides a natural heating source for the corona where relativistic electron-positron pairs are susceptible to upscatter disk photons via inverse Compton up to high energies. Its time scale is too short to account for the hour-long flares from SgrA* but for a stellar-mass BH, it corresponds to millisecond flares similar to the ones observed by Gierlinski et al. (2003) in Cygnus X-1. These dense, hot and macroscopic plasmoids could be responsible for enhanced localized emission as they propagate on a helicoidal trajectory. When seen face-on, they would mimic an orbiting hot spot similar to the one reported by The Gravity collaboration (2018).

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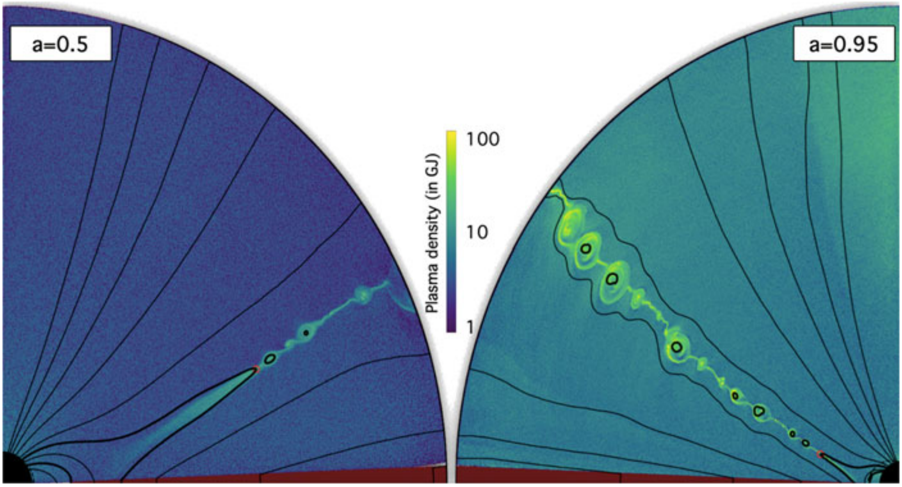

Figure 3. Charge density maps in units of Goldreich-Julian density for an intermediate (left panel) and high (right) BH spin. The disk is in red in the mid-plane. The poloidal magnetic field lines are in black and the red dot locates the Y-point on the separatrix i.e. the outermost closed magnetic field line. The dashed line is the ergosphere while the black disk is delimited by the event horizon.

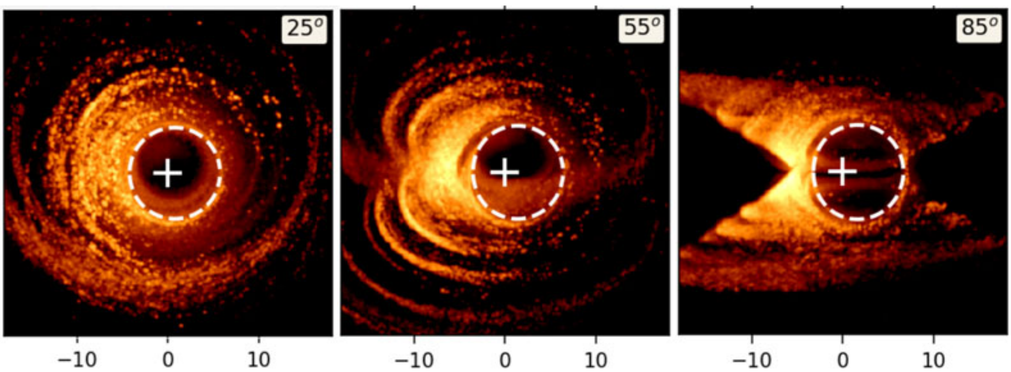

Figure 4. Intensity maps (logarithmic scale) for synchrotron emission from the current sheet, as seen from different viewing angles. The BH has a spin of 0.8 and is located at the white cross and its shadow is the white dashed line. The bottom axis is in units of r_g.

3.3. *Light emission*

Based on the kinetic energy distribution of particles in the current sheet, we derived synchrotron spectra for different BH spins. We identified a power-law component which could serve as the irradiating spectrum in order to lower the number of degrees-of-freedom of the X-ray reflection spectroscopy fits. Eventually, we computed synthetic synchrotron emission maps of the current sheet for different viewing angles using a forward ray-tracing version of the `geokerr` code (Dexter 2009), first used in Crinquand et al. (2021). In Figure 4, we can see arcs which are artefacts due to the axisymmetric assumption we rely on. However, for exposure times longer than a few hours, the current sheet would manifest itself as a hourglass-shaped bright region.

4. Conclusion

The corona around accreting BHs is a collisionless environment where non-ideal kinetic effects can be captured with PIC simulations. Closed and open magnetic field lines can

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co-exists, with some coupling the disk to the BH. While open magnetic field lines funnel a jet or a wind, the closed ones ensure energy and angular momentum exchanges between the BH and the disk. A current sheet forms above disks in prograde rotation around the BH where particles are accelerated via magnetic reconnection. Through synchrotron emission, they generate a high energy power-law component. Through inverse Compton, this population of non-thermal electrons and positrons provides a physically motivated irradiation source for hard X-rays above the disk, useful for reflection models. Episodic plasmoid ejection might explain millisecond flares observed in Cygnus X-1 in the high soft state. As they cascade back to the disk from the Y-point, relativistic particles could produce a hot spot at the footpoint of the separatrix.

5. Questions

Dmitry Bisikalo: What happens to the plasmoids as they move away from the BH?

Ileyk El Mellah: They progressively expand and dilute so their radiative efficiency drops.

Dmitry Bisikalo: Do you see collisions and shock waves between plasmoids?

Ileyk El Mellah: Good point. We do resolve secondary current sheets transverse to the first one which appear when two plasmoids collide in the main current sheet.

Christian Boily: What are your boundary conditions?

Ileyk El Mellah: Since the inner edge is within the event horizon, trivial boundary conditions (cancellation of electromagnetic fields and absorption of particles) are enough since no signal can propagate back above the horizon. At the outer edge, between 27 and $30r_g$, we have a buffer zone where particles are deleted and where the electromagnetic fields are damped.

Acknowledgments

This project has received funding from the European Research Council (ERC) under the European Union's Horizon 2020 research and innovation programme (grant agreement No 863412). Computing resources were provided by TGCC and CINES under the allocation A0090407669 made by GENCI. The authors thank Maïca Clavel, Antoine Strugarek, Guillaume Dubus and Geoffroy Lesur for fruitful discussions and constructive feedback.

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