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# PARTICLE ACCELERATION VIA MAGNETIC RECONNECTION NEAR SPINNING BLACK HOLES COUPLED TO A SURROUNDING DISK

I. El Mellah[1], B. Cerutti[1,], B. Crinquand[2] and K. Parfrey[3]

**Abstract.** Accretion and ejection have been found to be tightly linked around stellar-mass and supermassive black holes (BHs). The EHT results suggest that this junction is mediated by the intense and structured magnetic field within a few 10 gravitational radii. Since the seminal work by Blandford & Znajek in the 70's, most models of BH magnetospheres focused on a specific configuration where magnetic field lines threading the BH event horizon 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 disk and a hot corona threaded by a large scale magnetic field connected to the BH. I hereby report on recent results we obtained by performing global particle-in-cell simulations in Kerr metric to capture the dynamics of the electromagnetic fields and of the pair plasma in the corona. We find that a hybrid magnetic topology develops with: (i) magnetic loops connecting the disk to the event horizon, which enables energy and angular momentum exchanges between the 2 components, (ii) open field lines threading the horizon and funneling a Blandford-Znajek jet, and (iii) open magnetic field lines anchored in the disk and inclined enough to launch a magneto-centrifugal wind. Although the corona is essentially force-free, a Y-point at the intersection of these 3 regions seeds a current sheet where magnetic reconnection heats the corona. At the intersection of these regions, a Y-point seeds a current sheet where magnetic reconnection heats the corona and accelerates particles up to relativistic speeds, which provides a source of hard X-rays above the disk. Eventually, I will show particle energy distribution along with synthetic images and spectra of the synchrotron emission associated to this mechanism.

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

## 1 Introduction

Accreting black holes (BHs) are surrounded by a hot and diffuse corona where photons are upscattered by relativistic electrons up to gamma-ray energies. This high energy non-thermal component has been observed around a stellar-mass BH like the one in Cygnus X-1, both in the low-hard and the high-soft states (Cangemi et al. 2021). It supports the idea that the corona is collisionless. The situation is comparable around supermassive BHs like Sgr A$*$ from which we observed non-thermal flares in near infrared on a daily basis (Witzel et al. 2018).

These flares are produced by synchrotron emission which suggests that the emitting plasma is highly magnetized, in agreement with polarization measures in Cygnus X-1. Event Horizon Telescope Collaboration et al. (2021) measured a high degree of polarization of the emission around M87$^*$ which indicates the presence of a strong poloidal magnetic field permeating the plasma. This magnetic field is brought and sustained by the accreted material.

Last but not least, these BHs often launch jets which are thought to be powered by the rotational energy of the BH (Blandford & Znajek 1977, hereafter BZ jets). In Cygnus X-1, multiple diagnostics based on iron lines spectroscopy, X-ray continuum fitting or X-ray reflection spectroscopy reached the conclusion that the dimensionless BH spin $a$ might be extreme. A major limitation of the X-ray reflection spectroscopy method is

[1] Univ. Grenoble Alpes, IPAG-CNRS, 414 Rue de la Piscine, 38400 Saint-Martin-d'Hères, France
[2] Department of Astrophysical Sciences, 4 Ivy Ln, Princeton, NJ 08544, USA
[3] School of Mathematics, Trinity College Dublin

the lack of physical connection between independent degrees-of-freedom of the models which are the BH spin on one side, and the location and radiative properties of the illuminating source of hard X-rays on the other side. Since we do not know the mechanism responsible for the heating of the corona which upscatters the soft X-ray photons from the disk, the latter source is often assumed to simply be a point-source above the BH (the so-called lamppost model, Kara et al. 2019). The situation is less clear for Sgr A$*$ and M87$^*$ but the efforts carried by the EHT and GRAVITY collaborations might yield reliable measures in the years to come.

The topology of the magnetic field around a spinning BH can be twofold. Most studies considered open magnetic field lines either threading the event horizon or the accretion disk. It is a convenient configuration to study the launching of BZ jets (Tchekhovskoy et al. 2011) and magnetic reconnection in the equatorial plane between the inner edge of the accretion disk and the BH event horizon (Crinquand et al. 2021). Alternatively, magnetic field lines around a BH can also be closed, with loops anchored in the disk and threading the BH event horizon (De Gouveia Dal Pino & Lazarian 2005; Uzdensky 2005). In this presentation, we focus on the latter magnetic field topology.

Here, I report on global particle-in-cell (PIC) simulations of the dynamics of the plasma and the electromagnetic fields in the corona around the BH. I will stress on the key-role played by coupling magnetic field lines anchored at one end in the accretion disk and threading the BH event horizon at their other end.

## 2 Numerical setup

### 2.1 General relativistic PIC simulations

We use the fully relativistic PIC code GR-Zeltron (Parfrey et al. 2019). It solves the equations of Maxwell-Ampère and Maxwell-Faraday on a grid and of particle motion in a background fixed curved space-time set by the BH mass and spin. The electromagnetic fields are interpolated at the position of particles to compute the Lorentz force exerted on them. Current and charge deposit is non-conserving so a Poisson solver is used to enforce the Maxwell-Gauss equation. The staggered grid guarantees that the magnetic field remains divergence-free through the simulation.

### 2.2 Grid

The spinning BH is surrounded by an event horizon and an ergosphere. We work in Kerr-Schild coordinates such as we alleviate the coordinate singularity at the event horizon and go from 30 gravitational radii ($r_g$) all the way down an inner boundary located within the event horizon. We assume axisymmetry around the BH spin axis and symmetry with respect to the BH equatorial plane. The resolution is high enough such as we resolve the kinetic scales of the plasma we work with, in particular the Larmor radius.

### 2.3 Initial conditions

An electron/positron pair plasma is injected in the corona such as the density is high enough for the force-free regime to be achievable i.e. the density is above Goldreich-Julian everywhere (Goldreich & Julian 1969). The plasma is initially permeated by a magnetic field lines all threading the event horizon and anchored in an aligned and perfectly conducting disk in prograde Keplerian rotation around the BH. The magnetic field strength is such that the corona is highly magnetized ($\sigma >> 1$). The disk extends all the way down the innermost stable circular orbit (ISCO). The magnetic flux function on the disk is dipolar and field lines in the disk are frozen and forced to rotate at the local Keplerian angular speed. The disk is not accreting (i.e. there is no radial speed) and its dynamics is not resolved. Instead, it serves as a background boundary condition stationary over the duration of the simulation which remains short compared to accretion time scales. This configuration has been investigated in the past with force-free simulations which solved the general relativistic version of Grad-Shafranov equation using iterative relaxation methods (Uzdensky 2005; Yuan et al. 2019a). More recently, Yuan et al. (2019b) used resistive force-free simulations, where the topology of the initial guess for the magnetic field can change, in order to capture the current sheets and the twisted magnetic field lines which launch the BZ jet.

## 3 Magnetic field topology

This initial magnetic configuration is prone to a mechanism responsible for the formation of a current sheet in the corona (Uzdensky 2005). Indeed, if the BH spins, the initially poloidal magnetic field lines are twisted since

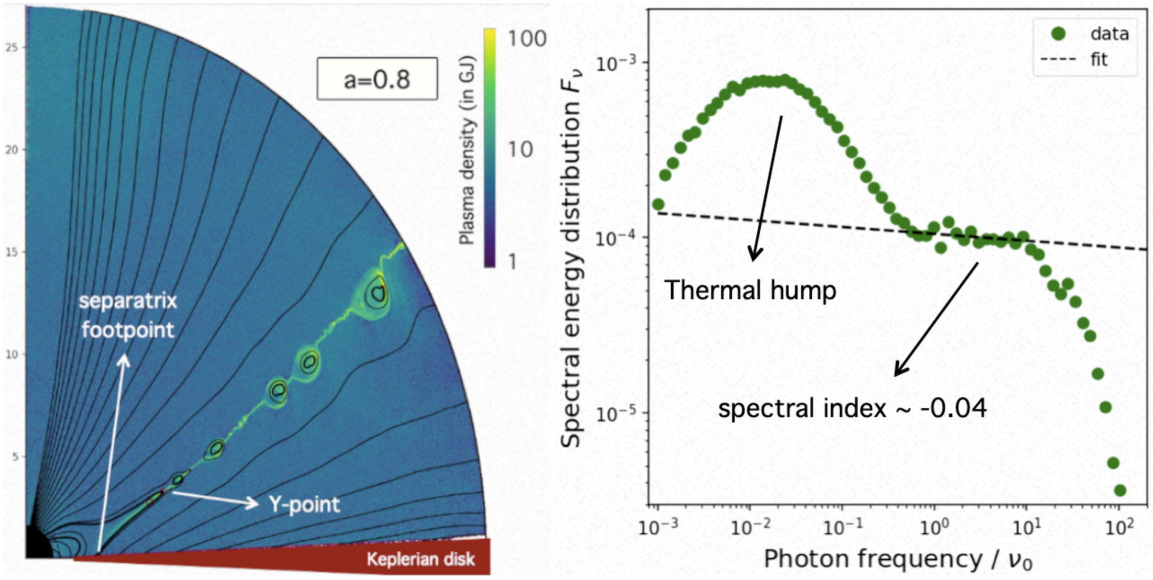


**Fig. 1. Left:** Numerical relaxed state with poloidal magnetic field lines and a colormap of plasma density (in units of Goldreich-Julian density). Macroscopic plasmoids are visible in the current sheet seeded at the Y-point on the separatrix. **Right:** Synthetic synchrotron spectrum from the current sheet with a thermal hump due to bulk motion and a power-law component produced by particles accelerated up to relativistic speeds via magnetic reconnection.

in the ergosphere, they experience frame-dragging while at their other end, on the disk, they rotate at the local Keplerian speed of their footpoint. A toroidal magnetic component develops, propagates outward and, beyond a certain distance, leads to the opening of the magnetic field lines. Only in the innermost regions the shear is low enough that magnetic tension can hold the field lines closed. It can be seen as the general relativistic analog to the light cylinder around a spinning neutron star, except that here (i) the outer light surface plays the role of the light cylinder and (ii) the magnetic field is sustained by the accretion disk, not by the compact object itself.

Regarding the magnetic field topology, four different regions appear (Fig 1, left panel). . First, between the event horizon and the outermost closed magnetic field line (hereafter the separatrix), a closed magnetosphere couples the BH to the disk. Second, among the magnetic field lines which open, there divide into two branches: those near the spin axis which thread the BH event horizon and those which are anchored in the disk beyond the separatrix. Last, a current sheet forms between the two last families of field lines, connected to a Y-point on the separatrix at its basis.

A 3D representation of the open magnetic field lines threading the BH event horizon reveals that they are strongly twisted. They rotate at a speed close to $\omega_{BH}/2 = (ac)/(4r_h)$, where $r_h$ is the radius of the event horizon and $c$ is the speed of light. This is the rotation speed expected from the balance between the spinning up of magnetic field lines from the ergosphere and the inertia of the plasma loaded at a density close from Goldreich-Julian values. It also happens to be the angular speed which gives the maximum jet power, for a given BH spin and magnetic flux, in the force-free limit. We computed the jet power by measuring the flux of the Poynting vector across the open magnetic field lines. Without surprise, we retrieve an evolution of the jet power with the BH spin which is in excellent agreement with the force-free formula, provided it accounts for higher order terms at high spin values (Tchekhovskoy et al. 2011). Similarly, the open magnetic field lines anchored on the disk are inclined enough to funnel a disk outflow via the magneto-centrifugal mechanism (Blandford & Payne 1982).

Apart near the Y-point, the closed magnetosphere is essentially force-free. For the BH spin values we explored ($a \geq 0.6$), energy and angular momentum flows from the BH to the disk along the coupling magnetic field lines. The rates are consistent with the values obtained in the force-free limit (Yuan et al. 2019a). This deposit of energy is susceptible to heat the regions of the disk coupled to the BH and increase their radiative flux, possibly producing a hot ring with an emission profile higher than what is expected from a classic Novikov-Thorne disk (Novikov & Thorne 1973). In the regime we looked at, angular momentum is deposited at rates too low to repel the accreted material and truncate the inner edge of the disk much beyond the ISCO.

## 4 Particle acceleration and synthetic observables

### 4.1 Magnetic reconnection

In the current sheet, the force-free approximation breaks up. Vivid magnetic reconnection dissipates the electromagnetic energy which serves to accelerate particles. Given the high magnetization $\sigma$, we retrieve a magnetic reconnection rate of $\sim 10\%$ independent of $\sigma$, in agreement with Werner et al. (2018). Plasmoids regularly form at the Y-point and the size they reach before being ejected along the current sheet is regulated by the tearing instability (Cerutti et al. 2013). The bulk motion of the plasmoids in the current sheet is mildly relativistic with a Lorentz factor $\Gamma \sim 2$. The higher the BH spin, the stronger the twisting of the magnetic field lines and the closer from the BH the Y-point lies. Consequently, for higher spins, reconnection occurs in a region of much higher magnetic field strength and electromagnetic energy is dissipated at higher rates. Once unfold in 3D, these axisymmetric simulations imply that particles are accelerated via magnetic reconnection along a Y-ring above the disk. This ring would be the privileged location of coronal heating and emission of hard X-rays from inverse Compton upscattering of soft X-ray photons from the underlying accretion disk.

### 4.2 Particle energy distribution and synthetic observables

The maximum particle Lorentz factor $\gamma$ in the current sheet increases with the BH spin. It contains a thermal hump around $\gamma \sim 2$ corresponding to the bulk motion but also a power-law component at higher Lorentz factors. The slope of the power-law is 0.9, close from what the 1.2 exponent expected from magnetic reconnection in the relativistic regime (Werner et al. 2018).

We used a forward ray-tracing version of the Geokerr code (Dexter & Agol 2009) described in Crinquand et al. (2021) in order to compute synthetic spectra and images of the synchrotron emission from the current sheet. We retrieve a power-law component at high energy consistent with being produced by the particles accelerated via magnetic reconnection (Fig 1, right panel). Synthetic images for different viewing angles are also available in El Mellah et al. (2022).

## 5 Conclusion and perspectives

The different regions are summarized in Fig 2 with (i) the open magnetic field lines threading the event horizon (in yellow), (ii) the open field lines anchored on the disk (in orange), (iii) the closed magnetosphere coupling the disk to the BH (in blue) and the current sheet (in green). The percents indicate the relative power of the jet, the energy deposit onto the disk and the reconnection mechanism in the current sheet, fairly independent of the BH spin for $a > 0.6$.

These results relate the BH spin to the location, shape and radiative flux and spectrum of the source of hard X-rays illuminating the underlying accretion disk. We find that this source is essentially a Y-ring which gets closer from the disk and the BH as the spin increases. It is important though to keep in mind that those results are also dependent on the magnetic flux distribution on the disk. We enforced a dipolar profile (i.e. $B_{pol} \propto r^{-3}$) but fits to observational results indicate that this profile is probably steeper than what is expected around SgrA$^*$ for instance (Chatterjee et al. 2021). A slower decrease of the strength of the poloidal magnetic field on the disk would result, at a given BH spin, in a more extended closed magnetosphere and a farther Y-ring, which would possibly increase the rates at which the BH can transfer energy and angular momentum to the coupled regions of the disk.

In the future, we plan to further investigate (i) the breaking up of the plasmoids in the azimuthal direction with 3D simulations, (ii) realistic particle injection procedures based for instance on pair-production from gamma-ray photons and (iii) the formation of this coupling configuration from the accretion of a magnetic loop.

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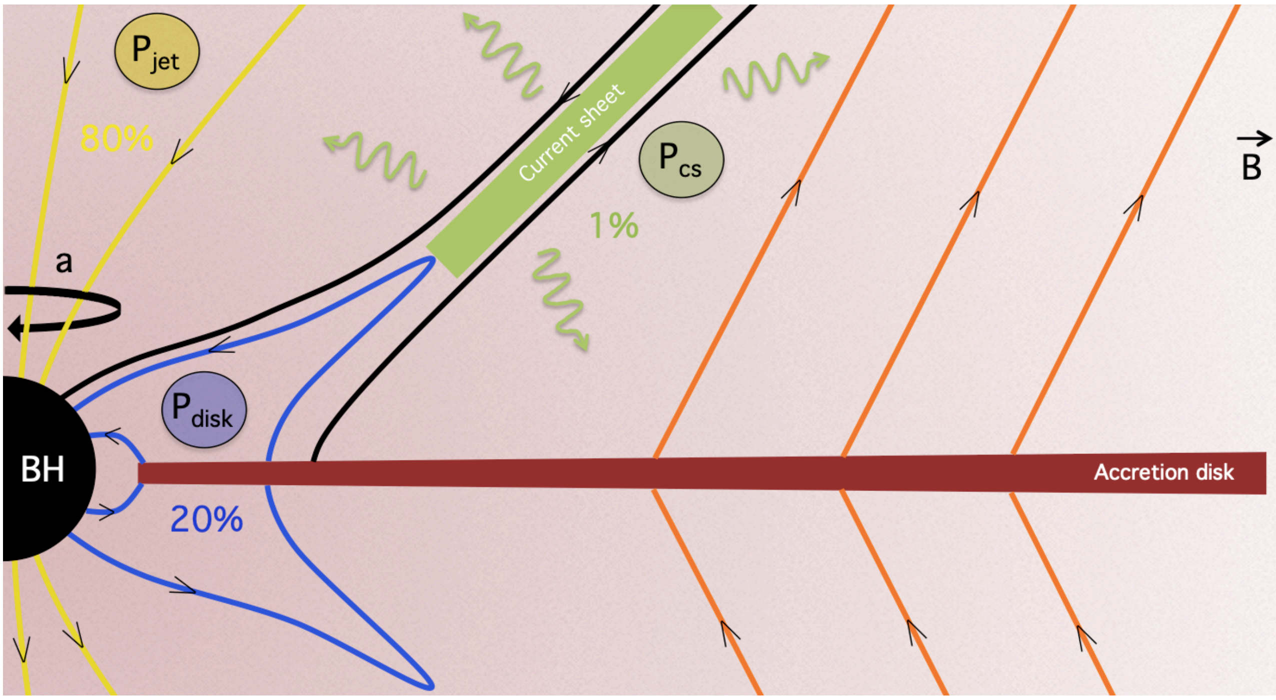


**Fig. 2.** Summary sketch with poloidal magnetic field lines and their polarity in each region. In the current sheet (in green), a fraction of the electromagnetic energy is tapped to accelerate particles via magnetic reconnection. They are the main source of radiation in the corona.


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