NUMERICAL STUDIES OF RELATIVISTIC JETS FROM BLACK HOLES

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Relativistic jets are powerful collimated outflows from accreting compact objects, especially spinning black holes. Jets, as well as their associated mechanisms of energy dissipation and particle acceleration, can be investigated by global or local numerical simulations using methods like general-relativistic magneto-hydro-dynamics (GRMHD), particle-in-cell (PIC), etc. This presentation highlights selected results from 3 projects related to relativistic jets.

GRMHD INVESTIGATION ON THE INITIATION OF MAGNETIC FLUX ERUPTIONS IN MAGNETICALLY SATURATED ACCRETION FLOWS ONTO KERR BLACK HOLES

WITH MATEUSZ KAPUSTA (OAUW) & AGNIESZKA JANIUK (CFT PAN)

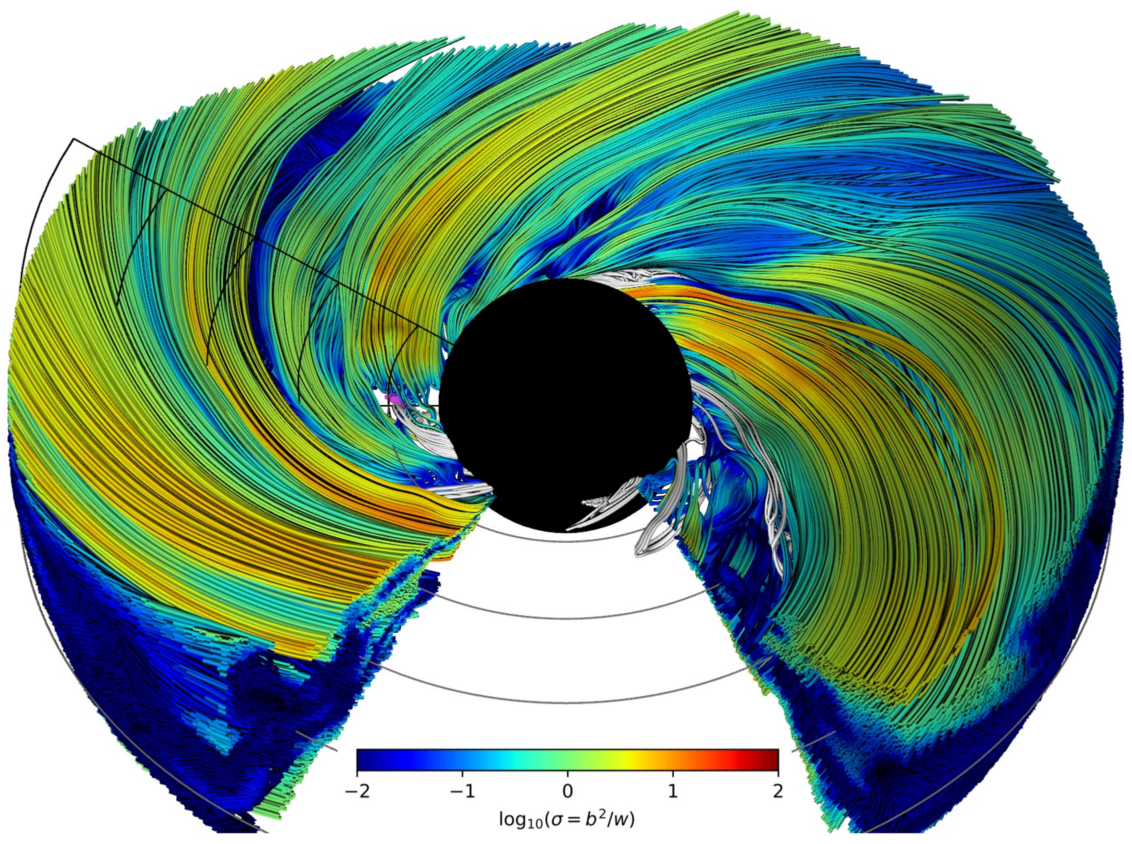

FIGURE 1: Selected magnetic field lines within $r \le 6M$ in prograde $a = 0.9$ case at onset of magnetic flux eruption ($t = 19594M$), colored by the magnetization parameter $\sigma = b^2/w$ (line colors are also affected by shading, with lines seen at small angles rendered darker). Shown are horizon-disconnected lines seeded at $r_0 = 5.9M$ for $\theta_{\rm L3,min} < \theta_0 < \theta_{\rm L3,max}$, seen from latitude $\theta_{\rm obs} = 45°$. A small but (θ_0, ϕ_0)-complete sample of doubly connected lines (closed loops with $\max(r) < 6M$) seeded at $r_0 = 1.42M$ (just under the horizon) are shown colored in white. The scene is seen from the same azimuth $\phi_{\rm obs} = 180°$; data for $150° < \phi < 210°$ (except for the doubly connected lines) are cut out to reveal (r, θ) sections. Black spheres indicate the outer horizon at $r_{\rm H} = 1.436M$. The grid of arcs marks the radii $r/M = 2, 3, 4, 5, 6$ in the equatorial plane $\theta = 90°$ (gray) and in the $\phi = 90°$ quadrant spanning the latitudes $\theta_{\rm L3,min} \le \theta \le \theta_{\rm L3,max}$ (black). A small magenta patch just to the left of the horizon marks relativistic temperature ($\log_{10} T \ge 0.5$).

Magnetized accretion flow onto a black hole (BH) may lead to the accumulation of poloidal magnetic flux across its horizon, which for high BH spin can power far-reaching relativistic jets. The BH magnetic flux is subject to a saturation mechanism by means of magnetic flux eruptions involving relativistic magnetic reconnection. Such accretion flows have been described as magnetically arrested disks (MAD) or magnetically choked accretion flows (MCAF). The main goal of this work is to describe the onset of relativistic reconnection and initial development of magnetic flux eruption in accretion flow onto magnetically saturated BHs. We analyzed the results of 3D general relativistic ideal magnetohydrodynamic (GRMHD) numerical simulations in the Kerr metric, starting from weakly magnetized geometrically thick tori rotating either prograde or retrograde. We integrated large samples of magnetic field lines in order to probe magnetic connectivity with the BH horizon. The boundary between magnetically connected and disconnected domains coincides roughly with enthalpy equipartition. The geometrically constricted innermost part of the disconnected domain develops a rigid structure of magnetic field lines – rotating slowly and insensitive to the BH spin orientation. The typical shape of innermost disconnected lines is a double spiral converging to a sharp inner tip anchored at the single equatorial current layer. The foot-points of magnetic flux eruptions are found to zip around the BH along with other azimuthal patterns. Magnetic flux eruptions from magnetically saturated accreting BHs can be triggered by minor density gaps in the disconnected domain, resulting from the chaotic disconnection of plasma-depleted magnetospheric lines. Accretion flow is effectively channeled along the disconnected lines toward the current layer, and further toward the BH by turbulent cross-field diffusion. Rotation of flux eruption foot-points may contribute to the variability of BH crescent images.

Nalewajko, K., Kapusta, M., & Janiuk, A. 2024, A&A, 692, A37

PIC SIMULATIONS OF RELATIVISTIC RECONNECTION PLASMOIDS, FOCUSED ON ENERGY DENSITY ENHANCEMENT DUE TO MAGNETIC TENSION

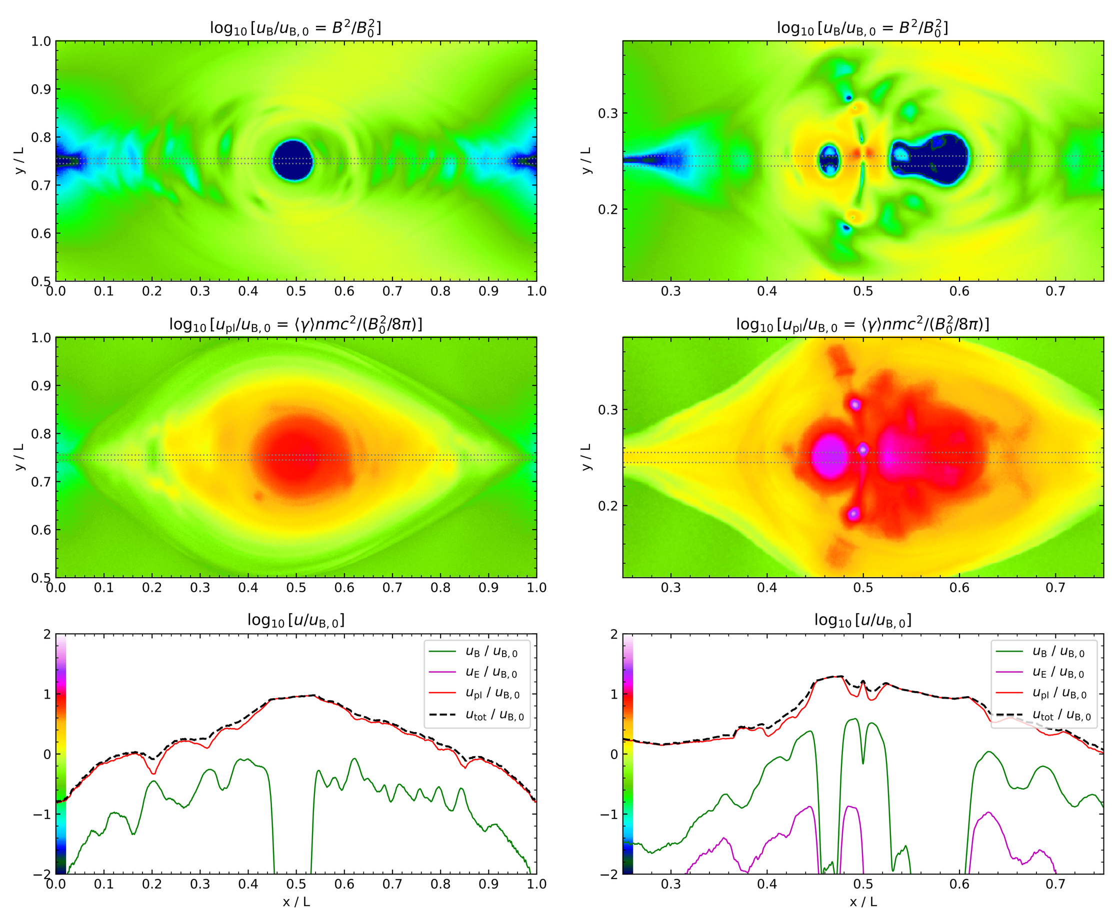

FIGURE 2: Maps $\log_{10}(u/u_{\rm B,0})(x, y)$ for magnetic energy density $u_{\rm B} = B^2/8\pi$ (upper panels) and plasma energy density $u_{\rm pl} = \langle\gamma\rangle nmc^2$ (middle panels). In the lower panels, we compare 1D energy density profiles of $(u/u_{\rm B,0})(x, y_0)$ measured along the strip indicated in the above maps by the dashed gray lines. A common color scale for all maps is referenced along the left axes in the lower panels. Here we present the case of no guide field for $\sigma_0 = 10$ and $L/\rho_0 = 1800$. The left panels show a relaxed monster plasmoid at the end of simulation; the right panels show a merger of large plasmoid.

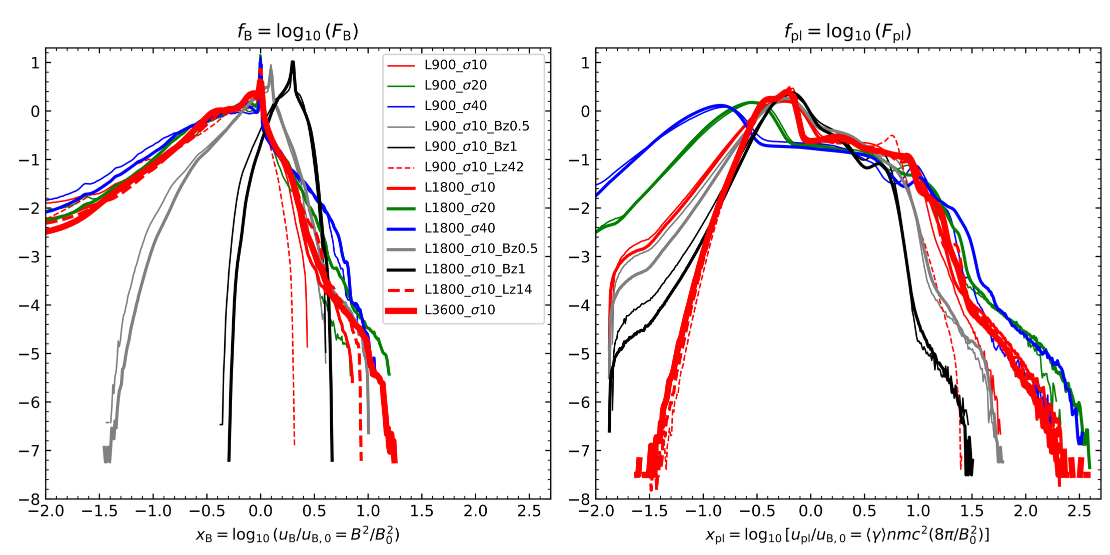

FIGURE 3: Logarithms $f = \log_{10}(F)$ of volume distributions $F(\mu) = {\rm d}F/{\rm d}\mu$ over argument $\mu = \log_{10}(u/u_{\rm B,0})$ with u the energy density: of magnetic fields $u_{\rm B} = B^2/8\pi$ (left panel), and of the plasma $u_{\rm pl} = \langle\gamma\rangle nmc^2$ (right panel). Functions $f(\mu)$ were averaged over the duration of each simulation.

Toroidal magnetic field is a key ingredient of relativistic jets launched by certain accreting astrophysical black holes, and of plasmoids emerging from the tearing instability during magnetic reconnection, a candidate dissipation mechanism in jets. Tension of toroidal field is an anisotropic force that can compress local energy and momentum densities. We investigate this effect in plasmoids produced during relativstic reconnection initiated from a Harris layer by means of kinetic particle-in-cell (PIC) numerical simulations, varying the system size (including 3D cases), magnetization, or guide field. We find that: (1) plasmoid cores are dominated by plasma energy density for guide fields up to $B_z \sim B_0$; (2) relaxed 'monster' plasmoids compress plasma energy density only modestly (by factor ~ 3 above the initial level for drifting particle population); (3) energy density compressions by factors $\gtrsim 10$ are achieved during plasmoid mergers, especially with the emergence of secondary plasmoids. This kinetic-scale effect can be combined with a global focusing of the jet Poynting flux along the quasi-cylindrical *bunched spine* (a proposed jet layer adjacent to the cylindrical core) due to poloidal line bunching (a prolonged effect of tension of the jet toroidal field) to enhance the luminosity of rapid radiation flares from blazars.

Nalewajko, K. 2025, A&A, accepted
https://users.camk.edu.pl/knalew/aa53662-25.pdf

ANALYSIS OF EXTREME-RESOLUTION GRMHD SIMULATION OF RELATIVISTIC JETS (PRELIMINARY)

WITH MATEUSZ KAPUSTA (OAUW), BART RIPPERDA (CITA) & ALEXANDER PHILIPPOV (MARYLAND)

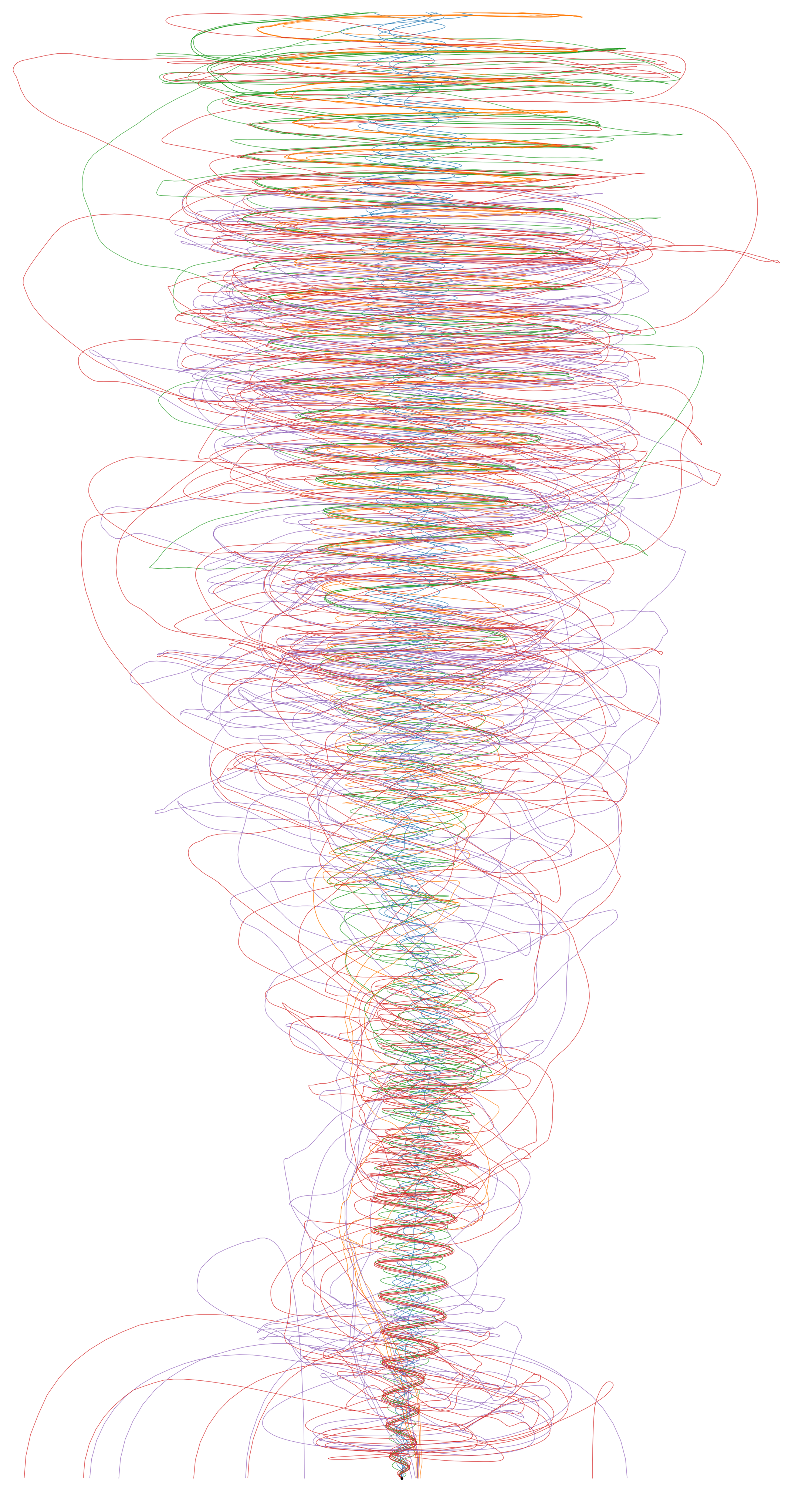

FIGURE 4: Relativistic jet sketched with 25 magnetic field lines connecting either: (1) black hole with top jet spine (blue), (2) black hole with top jet sheath (green), (3) black hole with torus (red), (4) hotspot with top jet sheath (orange), (5) hotspot with torus (purple). The vertical scale of this image is $\sim 1800 R_g/c$ (the black hole is indicated in the bottom). A distortion in the jet structure can be seen roughly at $1/3$ of jet length from the bottom, it is an echo of past magnetic flux eruption. Note that red lines leave the jet spine below the distortion, and orange lines enter the jet spine above the distortion. The distortion is predicted to have distinct radiative and especially polarimetric properties, potentially appearing as a superluminal radio knot.

We investigate the influence of magnetic flux eruptions on the structure of the relativistic jets and the magnetically saturated accretion flow (MAD) with the help of extreme-resolution (effectively $5376 \times 2304 \times 2304$ cells) general relativistic magneto-hydro-dynamical simulations first presented in Ripperda et al (2022, ApJ, 924, L32). We investigate the 3D structure of jets, including the axisymmetric component as well as departures from axisymmetry, to distances of $\sim 10^3$ gravitational radii at different stages in the cycle of magnetic flux accumulation and eruptions. The impact of external magnetic flux tubes on the jet structure is particularly strong after a major eruption weakens the jets. We trace extensive samples of magnetic field lines to examine the magnetic connectivity between the jets, the wind, the accretion flow and the hotspots ejected from the jet during eruptions. We describe how the ejected magnetic flux tubes connect equatorial hotspots with the jet spine/sheath while crossing the wind region at various post-eruption stages.

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