Global numerical simulations of relativistic jets

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Abstract for the general public

The goal of the project is to study the structure of relativistic jets (formed in the vicinity of spinning black holes) using global numerical simulations solving the equations of magneto-hydrodynamics (MHD) in general relativity (GR). Such jets are observed in certain active galaxies (galaxies with active nuclei in which supermassive (billions of solar masses) black holes accrete large amounts of magnetized gas), particularly radio galaxies (e.g. M87, known from the first ring image of a black hole) and blazars (having a jet pointed to us; its emission is relativistically amplified thousands of times), as narrowly collimated powerful outflows propagating at relativistic speeds (close to the speed of light), bright sources of non-thermal emission extending from radio to gamma rays (~16 decades in photon energy). Global simulations follow jets all the way from the black hole horizon, including GR. Such outflows start as rotating magnetospheres anchored to the black hole, they gradually accelerate and collimate over 3-5 decades in distance, in the largest radio galaxies reaching distances of 9 decades. They are subject to internal instabilities and boundary interactions that ensure effective energy dispersion and particle acceleration, but do not lead to jet disruption.

Relativistic jets are roughly axisymmetric, however, both observations, theory and simulations point to an important role of asymmetric structures, hence most of our simulations will be 3D. We will work with a leading international team to analyze the results of their highest-resolution 3D GRMHD simulation, which shows the structure of jets in great detail, including the effects of instabilities and boundary interactions. We will also perform new GRMHD simulations using publicly available codes and computational resources available in Poland and Europe.

<u>Relativistic jets in quasars.</u> Quasars are active galactic nuclei with very bright thermal emission from thin accretion disks. Some quasars produce relativistic jets, and may also be bright blazars. How a jet can be collimated in the presence of a thin disk remains a mystery. A new class of so-called "puffy" accretion flows including thin disks has recently been discovered, and they may provide a solution to the problem of quasar jets. We will perform new GRMHD simulations involving dynamically important radiation to study the collimation of jets by such accretion flows, and the effect of radiation from accretion flows on jet dynamics and blazar emission.

<u>Magnetic polarity reversal.</u> Relativistic jets carry large magnetic fluxes inherited from accretion flows. Magnetic polarity can sometimes be reversed in an accretion flow, switching off one jet and launching another with reversed polarity. This will form a gap propagating along the jet, visible as a bright superluminal knot. We will perform new GRMHD simulations of accretion flows with two magnetic field loops, investigating how the magnetic polarity reversal works in the region of jet formation, how the resulting gap propagates along the jets, how its width evolves with distance, and whether a new jet can come into contact with an old one, inducing magnetic reconnection between them.

<u>Measuring relativistic jets at extreme resolution.</u> We will analyze the results of the state-of-the-art GRMHD simulation of relativistic jets covering 3 decades of distance in 3D. We will measure the shape of the jet (its axis and cross sections), the extent to which it departs from axial symmetry, what are the implications for acceleration and boundary interactions. We will measure how the jet bends and precesses, what are the consequences for relativistic radiation, jet images, their variability. We will also measure the structure of magnetic and velocity fields across the jet.

<u>Echoes of magnetic flux eruptions.</u> Magnetic flux eruptions are produced by accreting black holes producing jets and saturated with magnetic flux. They can temporarily double the magnetic flux of jets, which is an alternative to magnetic polarity reversal for disrupting jets and producing superluminal knots. We will analyze the results of the state-of-the-art 3D GRMHD simulation of relativistic jets, examining how a major magnetic flux eruption perturbs the jets, how this perturbation travels along jets, what are the consequences for other physical processes.