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Summary of Previous and Current Research

Studying accretion disks around compact objects has been my primary research interest. Recently, I have been mostly involved in developing radiative fluid dynamics codes in general relativity and applying them to simulating black hole (BH) accretion disks. Earlier on, I developed theoretical models and provided stationary and time-dependent numerical, one-dimensional, solutions of relativistic, transonic and advective BH accretion disks. Other points of my interest were related to outflows of mass and energy from such objects, the G2 cloud approach to the Galactic center, ejection mechanisms of relativistic jets, thermal stability of accretion disks, and black hole population synthesis. Below I list, in reverse chronological order, the most important projects I led or took part in.

- Simulating super-critical accretion in general relativity - Very recently, I have applied the KORAL code (see next bullet) to the BH accretion problem (Sądowski et al. 2013c). I simulated axisymmetrical models of optically thick accretion disks with accretion at the level of $100\dot{M}_{\rm Edd}$ around BHs with spin $a_* = 0.0$ and 0.9. I have shown that the $a_* = 0.9$ disk generates significant outflows of energy and mass driven by the BH rotational energy. The radiation is mostly trapped in the flow and advected into the BH. See Fig. 1.

- Developing radiative fluid dynamics code in general relativity - Simulating accretion disks with moderate and large accretion rates requires methods able to handle both optically thin and thick regions. I have developed the very first general relativistic code satisfying this condition — KORAL (Sądowski et al. 2013a). I implemented the M1 closure scheme in a covariant form and proved that it is robust in strong gravity. Recently, I have included the evolution of magnetic fields making self-consistent simulations of accretion disks with radiation possible.

- Simulating the effect of the Sgr A* accretion flow on the appearance of G2 after pericenter - A gaseous object, called the G2 cloud, is approaching the Galactic center along a very elongated orbit with pericenter radius deep inside the Bondi radius. The cloud density and angular momentum are comparable with the corresponding parameters of the innermost region of Sgr A* atmosphere. We considered how the accretion disk affects the dynamics of the cloud and its appearance on the sky. We predicted that the spatial distribution of emission and the shape of position-velocity diagrams

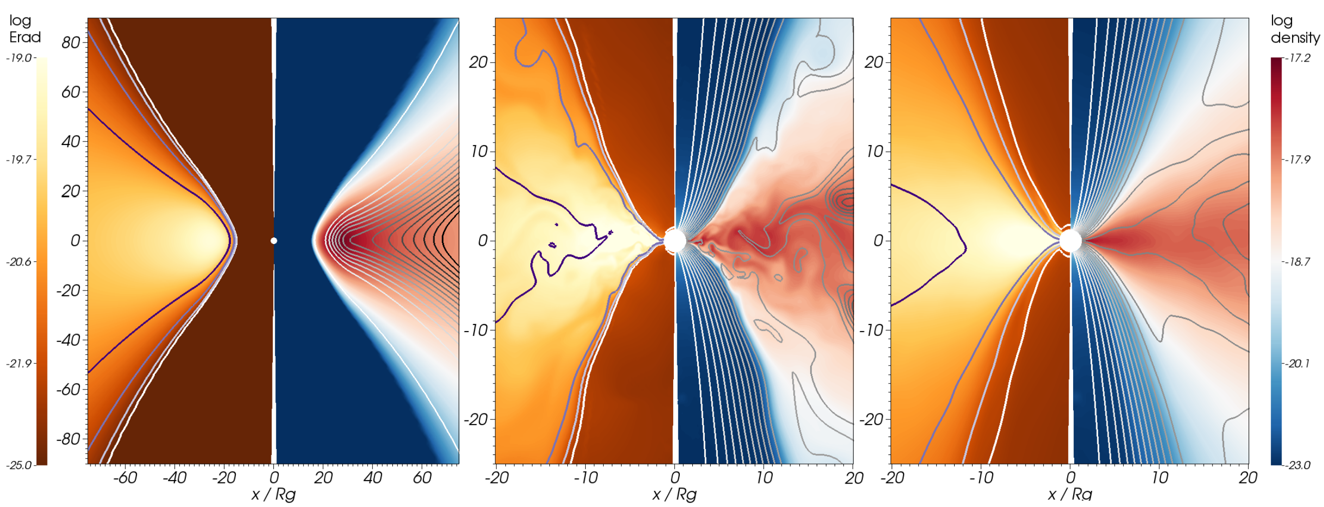

Figure 1: Initial (left), snapshot after $t = 10000\,GM/c^3$ (middle), and averaged over $t = 2000 \div 12000\,GM/c^3$ (right panel) disk structure in the $\dot{M} \approx 100\dot{M}_{\rm Edd}$, $a_* = 0.9$ simulation. In each panel, the left half shows the radiative energy density in the comoving frame (colors) and the total optical depth (contours), and the right half shows the density (colors) and magnetic field lines (contours).

depend significantly on the orientation of the accretion flow with respect to the cloud orbit (Abarca et al. 2013). In this project I supervised undergraduate student David Abarca.

- Predicting G2 bow-shock radio emission - The G2 cloud moves supersonically through the accretion flow of Sgr A* plowing its gas and forming a bow-shock. Electrons are effectively accelerated to relativistic energies and are expected to emit synchrotron emission with the maximum flux around 1 GHz. Using one of the long-duration simulations of thick disks as a model for Sgr A*'s accretion flow, I calculated radio light curves, the spectrum of radio emission and their dependence on the cloud and disk parameters (Sądowski et al. 2013b,c). The lack of significant emission provides constraints on these parameters, suggesting possibly lower than expected atmosphere density at the radii of interest.

- Numerical studies of thick accretion disks and emerging outflows - Using a general relativistic magnetohydrodynamic code `HARM`, I performed a set of long-duration simulations of geometrically thick (optically thin) disks around both non-rotating (Narayan et al. 2012) and spinning (Sądowski et al. 2013d) BHs. We studied the structure of the accretion flows, and put most attention to the amount of mass, energy, and momemtum leaving the disk. We showed that the energy outflow is confined to the jet region, while the wind carries most of the mass and momentum and covers larger solid angle potentially providing efficient feedback on a wide range of scales inside the host galaxy. We gave empricical formulae for the outflow rates in the jet and wind.

- BH spin evolution - I studied the spin evolution of BHs accreting at supercritical accretion rates (Sądowski et al. 2011). I showed that the terminal spin value depends significantly both on the assumed value of the α parameter and the accretion rate, and may range between $a_* = 0.98 \div 0.9995$ (Fig. 2).

- Thermal instability and limit cycles - I constructed a model for time-evolution of relativistic, transonic, advective accretion disks using 1.5 dimensional dynamics. The equations were solved with spectral methods and the obtained limit cycle behaviour around Kerr BHs was studied (Xue et al. 2011).

- `slimbb` - Relativistic slim disk solutions were used to construct the XSPEC `slimbb` package which generalizes the popular `kerrbb` model to the regime of high, even super-Eddington, accretion rates (Straub et al. 2011).

- Relativistic slim disks - I developed new efficient numerical methods for solving the equations of relativistic slim disks (Sądowski 2009) using the relaxation approach. In this way I was able to obtain a full spectrum of solutions for the whole range of accretion rates and BH spin. Subsequently, I developed a scheme coupling the radial and vertical structures of relativistic slim disks, eliminating arbitrary factors which influence solutions of the usual polytropic slim disk models.

- Acceleration of jets - I studied the centrifugal mechanism of jet acceleration in general relativity by studying kinematics of test particles in the force-free magnetosphere approximation (Sądowski & Sikora 2010). We showed that in the vicinity of fast rotating black holes jets can be launched centrifugally by cold, magnetized disks even for nearly vertically shaped magnetic flux surfaces.

- BH population synthesis - Using the `startrack` population synthesis code, I studied populations of black holes in our galaxy (Belczynski et al. 2004) as well as initial populations of black holes in globular clusters (Belczynski et al. 2006). The latter were used as initial conditions for studying the rate of compact object mergers in globular clusters and for predicting LIGO detection rates (Sądowski et al. 2008).

- Martian southern polar cap - I analyzed gravitational data from the Mars Global Surveyor. I was able to estimate the range of possible densities of the southern Martian polar cap by comparing the gravitational and topographical models of the Martian surface. We proved that the polar cap must contain a significant fraction of water (Sądowski & Zuber 2002).

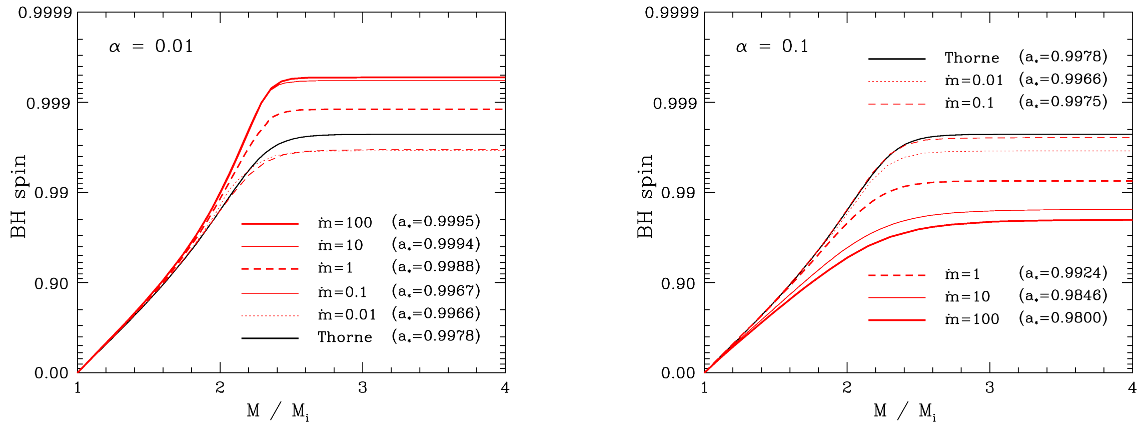

Figure 2: Black hole spin evolution for $\alpha = 0.01$ (left) and 0.1 (right panel) for different accretion rates as a function of the accreted mass. The evolution in the case of a standard thin disk is shown by the black solid line (Sądowski et al. 2011).

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