PhD Open Days

Dynamics of magnetospheres of rotating compact objects with General Relativity

Advanced Program in Plasma Science and Engineering / APPLAuSE

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Motivation

Understanding some of the most extreme events in the Universe

Compact objects have been known to play a role in the most violent space events, such as active galactic nuclei (AGN) jets and gamma-ray bursts [1]. Due to their complex and extreme nature, they combine sub-fields as:

- **General Relativity** (GR);
- **Quantum Mechanics**;
- **Plasma Astrophysics**.

Ongoing campaigns such as the **Event Horizon Telescope** and **GRAVITY**, aim at resolving horizon-scale structures of the **supermassive black hole** at the centre of our galaxy and M87.

Global models of compact objects (pulsars [2,3] and rotating black holes [4]) and their active **magnetospheres** are required to fully understand how **microscopic physical processes** (QED) and **space-time curvature** (GR) affect self-consistently the macroscopic magnetosphere dynamics.

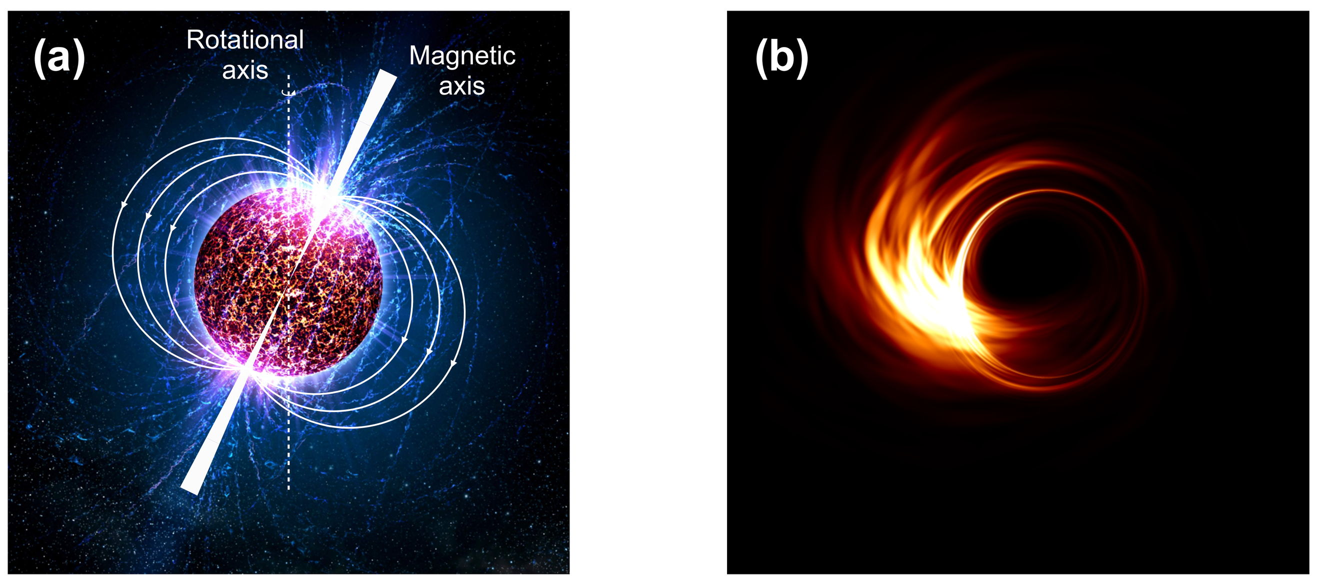


Figure 1: (a) Illustration of a neutron star with a schematic of the magnetic field lines. **(b)** Observational appearance of an accretion disk from a rotating black hole. Credit: Reed, C. Penn State University (2009) and Hotaka Shiokawa.

State-of-the-art

From neutron star to black hole magnetospheres

1967-68: Observation of rapidly pulsating radio sources.
1969: First global studies of pulsar magnetospheres (Goldreich and Julian):

- Star rotation induces an electric field capable of **pulling charged particles from its surface**;
- Magnetosphere filled with plasma;
- **Rotational energy** and **angular momentum** extracted due to electromagnetically driven wind.

1974: Vacuum solution for Maxwell's equations in **Kerr space-time coordinates** (Wald).
1977: Blandford-Znajek mechanism explains black hole jet launching and rotational energy extraction due to plasma-filled magnetosphere.

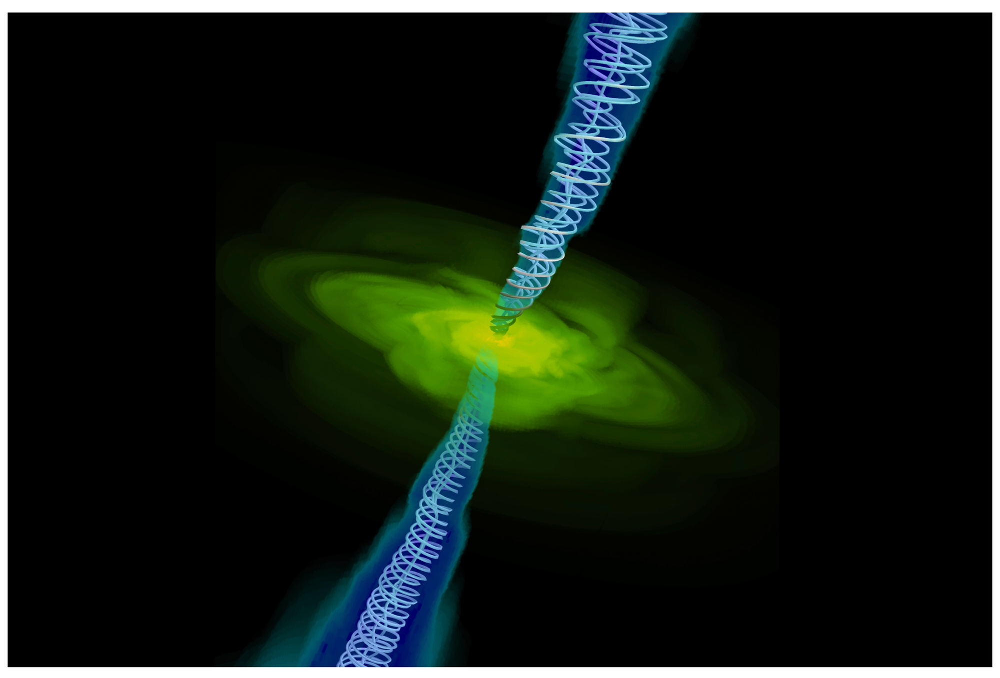


Figure 2: Magnetic field lines of an accreting black hole. Credit: Alexander Tchekhovskoy, Lawrence Berkeley National Laboratory (2014).

Numerical methods

Force-free MHD models

Used to model global dynamics of pulsars and rotating black holes

- Resistive MHD (RMHD)
- Full relativistic MHD
- General relativistic MHD (GRMHD)

Contributions: Leveraged the understanding of black hole accretion and jet production, as well as global pulsar magnetosphere dynamics.

Disadvantages:

- Unable to **track acceleration mechanisms** that lead to the observed radiation spectrum.
- Do not take into account **pair production** and **radiation reaction** in ultra-intense electromagnetic fields in a **self-consistent way**.

Fully kinetic Particle-in-Cell (PIC) simulations

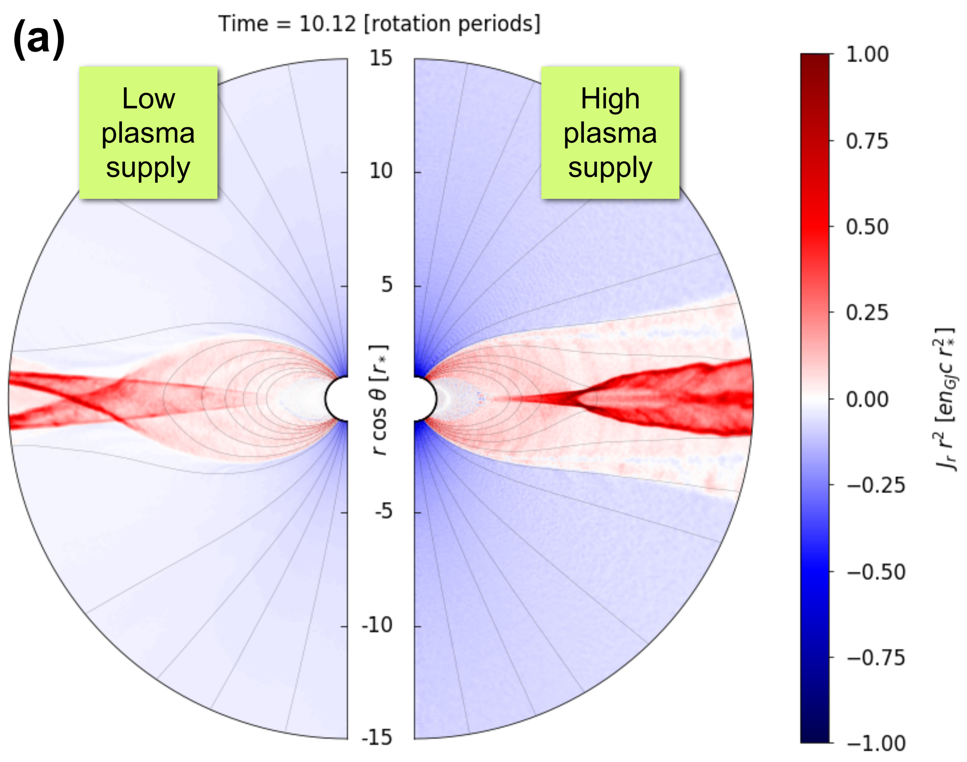
Astrophysical community:

- Pair production and GR corrections considered.
- Aligned, oblique and binary pulsar global models.
- **Do not conserve charge and artificial particle injection mechanisms.**

OSIRIS @ IST [5]:

- QED [6] and radiation reaction modules.
- Charge conserving scheme.
- Radiation diagnostics.
- **Upgrade to GR curved space-time is under development.**

(a)



(b)

Maxwell's equations with GR

$$\left(\nabla \times \left(\alpha \mathbf{E} + \frac{\boldsymbol{\beta}}{c} \times \mathbf{B}\right)\right) = -\frac{1}{c}\frac{\partial \mathbf{B}}{\partial t}$$

$$\left(\nabla \times \left(\alpha \mathbf{B} - \frac{\boldsymbol{\beta}}{c} \times \mathbf{E}\right)\right) = \frac{1}{c}\frac{\partial \mathbf{E}}{\partial t} + \alpha \mathbf{j} - \rho \boldsymbol{\beta}$$

Particle pusher

Boundary conditions

New $\gamma\gamma$ pair production module

Figure 3: (a) Current density of an axisymmetric global pulsar simulation for a low and high plasma injection from the star surface. Credit: Fábio Cruz @ GoLP, IST. **(b)** Modifications to be implemented in the OSIRIS framework.

Scientific goal

- Shed light on the **gravitational frame dragging effects** in macroscopic plasma dynamics in the vicinity of **compact objects**.
- Develop a novel **GR-PIC module** within OSIRIS framework to self-consistently study the evolution of the magnetospheric plasma in **extreme environments**, showing the interplay between the **microscopic** and **macroscopic** processes.
- Identify key particle accelerating and rotational energy extraction mechanisms.

References and Acknowledgments

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FCT Fundação para a Ciência e a Tecnologia

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