General relativistic particle-in-cell simulations of neutron star magnetospheres

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Polar cap emission and general relativity

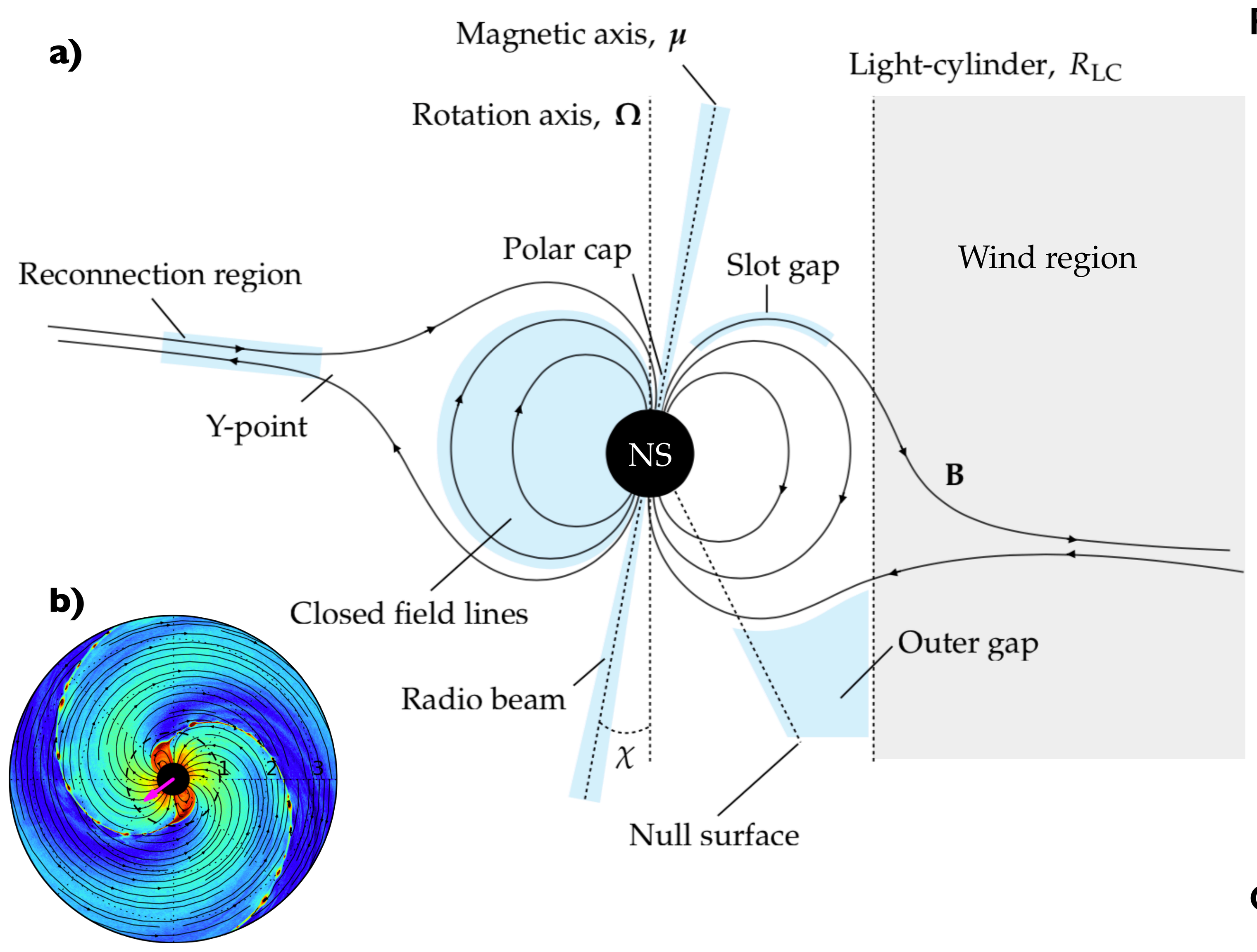

Figure 1: a) Schematic representation of a pulsar magnetosphere (top); **b)** Equatorial plane view of an orthogonal rotator [3] (bottom).

Previous works:

e.g. [1,2] The schematic in Fig. 1a shows a typical magnetospheric solution for MHD and FF models when threaded by a dipolar magnetic field and high plasma supply.

Rigid co-rotation beyond the light-cylinder would require particles to travel faster than the light speed. A toroidal component of the magnetic field is induced due to the plasma inertia in the wind region - see Fig. 1b.

[4,5] Particle-in-cell (PIC) simulations have shown that the general relativistic (GR) frame-dragging effect is essential for the existence of pulsar mechanism for low obliquity rotators ($\chi \lesssim 40°$).

The appearance of a super-Goldreich-Julian (GJ) current density along the magnetic field lines is thought to activate the polar cap (PC) discharge [6]. Flat spacetime simulations show weak particle acceleration and no pair production in the bulk of the PC.

[7,8] Axisymmetric FF analytic models including GR showed that pair production operates only in a fraction of the PC and confirmed the presence of spacelike current, suggesting this as a key factor for pulsed radio observations.

Goal: The goal is to gain a deeper understanding of the magnetospheric emission. The focus of this work are neutron stars in the aligned rotator configuration.

Novelty: We study the global NS magnetosphere including all GR effects in the fields and particles.

OSIRIS-GR Implementation

The Kerr metric in the slow-rotation approximation and in spherical coordinates is

$$\mathrm{d}s^2 = \alpha^2\left(c\mathrm{d}t\right)^2 - \alpha^{-2}\mathrm{d}r^2 + r^2\left(\mathrm{d}\theta^2 + \sin^2\theta\mathrm{d}\phi^2\right) - 2\omega_{LT} r^2 \sin^2\theta\,\mathrm{d}\phi\,\mathrm{d}t$$

$$\alpha \equiv \sqrt{1 - R_s/r} \qquad \omega_{LT} \approx \frac{2I_*\Omega G}{c^2 r^3} \qquad R_s = \frac{2GM}{c^2} \qquad \boldsymbol{\beta} \equiv -\omega_{LT} \times \boldsymbol{r}$$

In the 3+1 formalism [9], Maxwell equations and the particle equations of motion are

$$\nabla \times \left(\alpha \boldsymbol{E} + \frac{\boldsymbol{\beta}}{c} \times \boldsymbol{B}\right) = -\frac{1}{c}\frac{\partial \boldsymbol{B}}{\partial t} \qquad \frac{d\boldsymbol{r}}{dt} = \alpha \boldsymbol{v} - \boldsymbol{\beta}$$

$$\nabla \times \left(\alpha \boldsymbol{B} - \frac{\boldsymbol{\beta}}{c} \times \boldsymbol{E}\right) = \frac{1}{c}\frac{\partial \boldsymbol{E}}{\partial t} + \frac{4\pi}{c}\left(\alpha \boldsymbol{j} - \rho \boldsymbol{\beta}\right) \qquad \frac{d\boldsymbol{p}}{dt} = \alpha q\left(\boldsymbol{E} + \frac{\boldsymbol{v}}{c} \times \boldsymbol{B}\right) + \alpha m \Gamma \boldsymbol{g} + \alpha \overleftrightarrow{\boldsymbol{H}}\boldsymbol{p} + \mathscr{F}_{RR}$$

Physical quantities are measured by the zero angular momentum observers (ZAMOs).

Charge is conserved in every timestep via a newly developed charge conserving scheme [10].

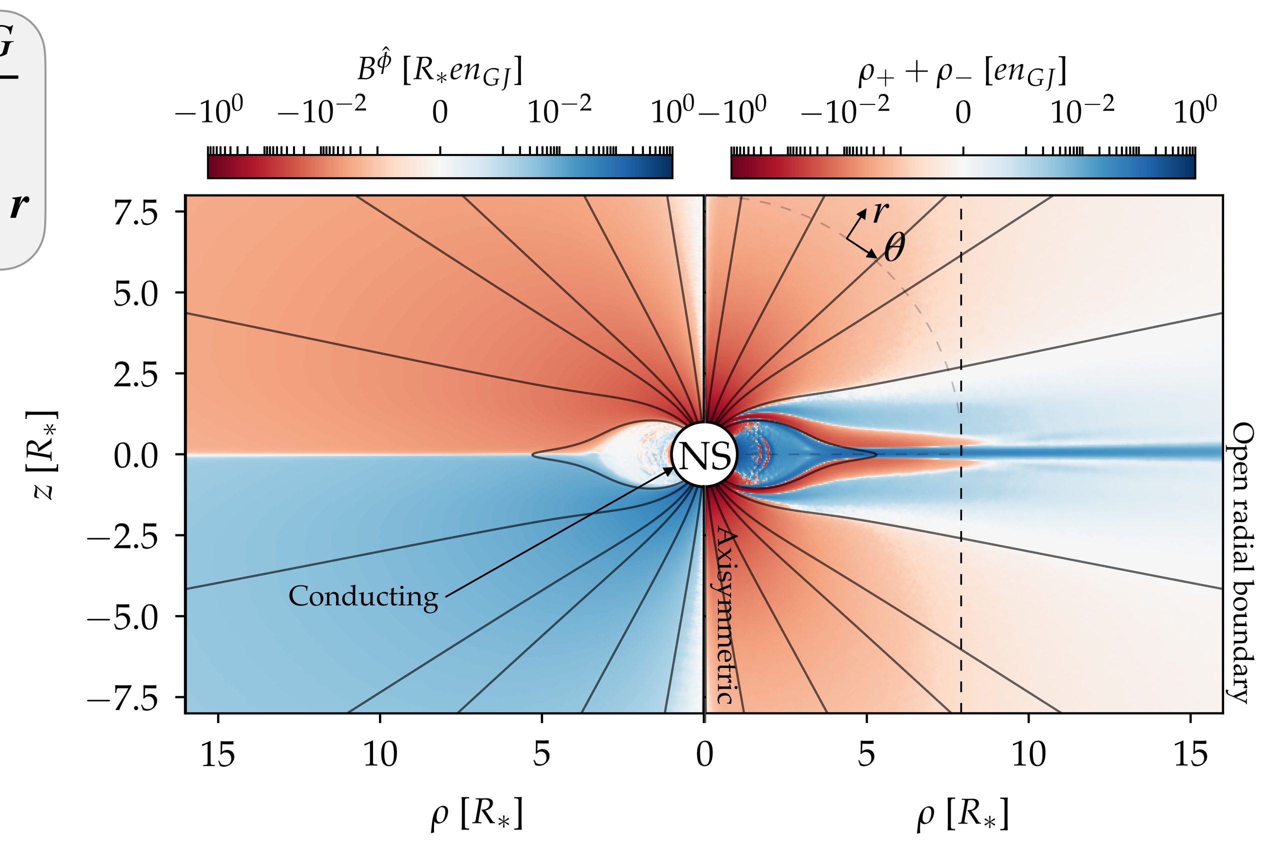

Figure 2: Toroidal magnetic field and plasma charge density with considered electromagnetic field boundary conditions.

Spacelike current leads to PC ignition

The FF magnetospheric solution is reproduced by PIC simulations when plasma is volumetrically injected in the whole magnetosphere [4]. When supplied from the stellar surface, the solution tends to be charge separated.

Gravitational forces act as a continuous drag on particles which may limit the amount of supplied plasma or reduce the current carried by each macro-particle, thus influencing the final solution state (hybrid regime).

In the FF regime, the magnetosphere converges to a steady state where the local poloidal electric field matches the globally imposed toroidal magnetic field:

$$j_\parallel^{PC} \approx j^{\hat r} \sim \frac{B^{\hat\phi}}{E^{\hat\theta}} j_{GJ} \lesssim j_{GJ} \xrightarrow[\text{frame-dragging effect}]{\text{w/ GR}} j_\parallel^{PC} \gtrsim j_{GJ} \quad \text{or} \quad j_\mu j^\mu \approx -\left(\rho v\right)^2 + j^{\hat r 2} > 0$$

The magnetosphere requires the counter-propagation of electrons and positrons to sustain the spacelike current, being the positrons provided as a consequence of the PC discharge (via pair production or surface injection). The PC ignition occurs due to the appearance of a stationary parallel electric field when $j_\parallel \gtrsim j_{GJ}$ [6].

The fraction of spacelike region is underestimated by FF models by $\sim 10\,\%$ for high compactness values [8]. This discrepancy may be justified by suppression of the volume-distributed return current [4] or by the sensitivity of the solution to the plasma injection mechanism.

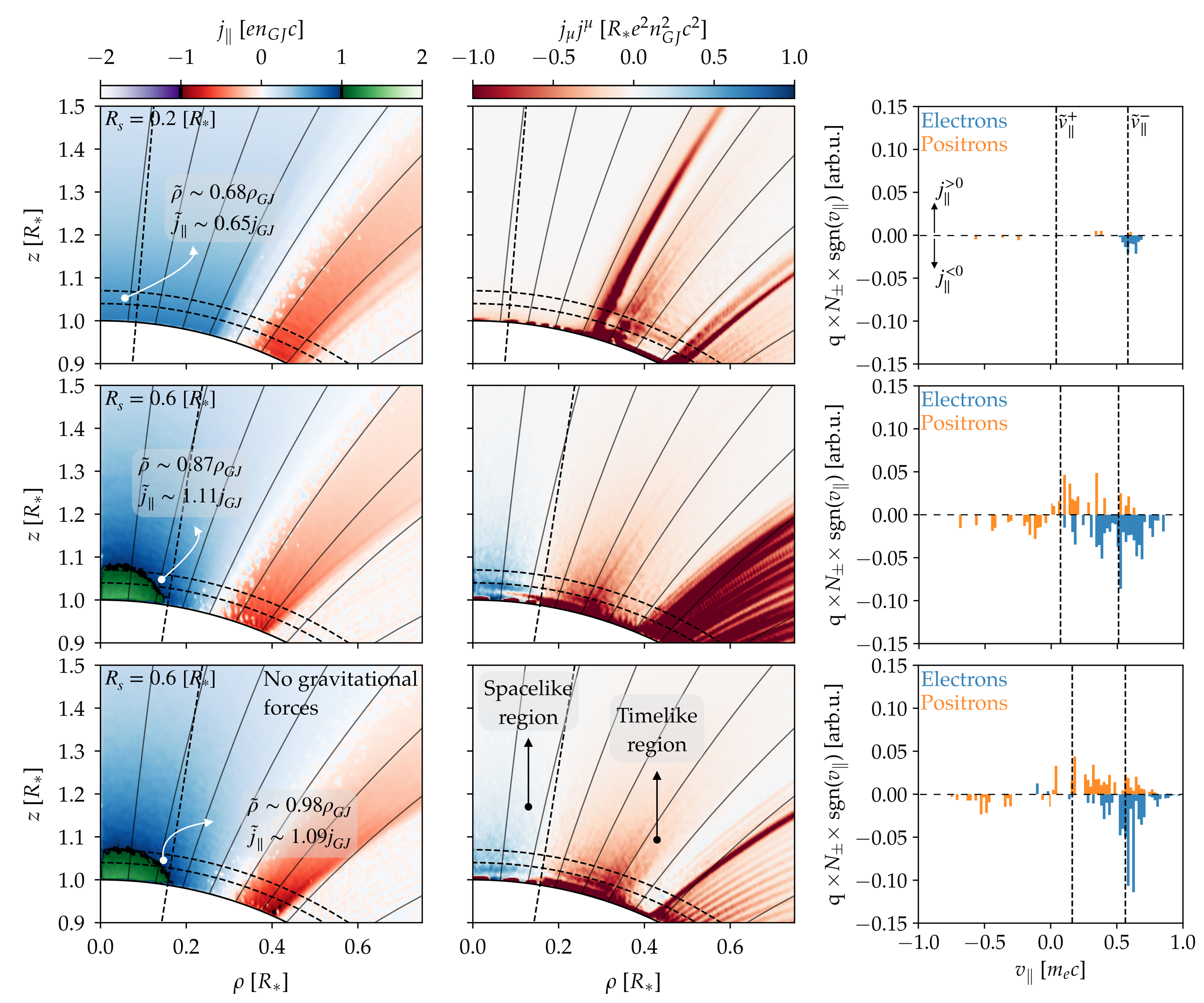

Figure 3: Parallel and 4-norm of the current density along with electron and positron distributions acquired on the accelerating region of the neutron star PC. The magnetic moment of the NS is maintained constant.

Conclusions

We confirm the presence of a spacelike current in the PC for a hybrid plasma supply regime

- Gravitational forces limit the range of parameters for which FF solutions are possible (initial kick required).
- The super-GJ current is supported mostly by mildly relativistic electrons and counter-propagating positrons.
- The percentage of the spacelike region is underestimated by FF models by $\sim 10\,\%$ for high compactness values. However, we see a suppression of this region for low compactness values ($R_s \lesssim 0.4 R_*$) in accordance with [4].

References

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