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NUMERICAL SIMULATIONS OF OBLIQUE ELECTROSPHERES WITH REALISTIC PARAMETERS BASED ON "PULSAR AROMA"

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Abstract. The structure of neutron stars electrospheres covering a large range of realistic parameters is investigated thanks to the development and use of a numerical simulation code named *Pulsar ARoMa*.

Keywords: neutron star, electrosphere, pulsar, numerical simulation

1 Introduction

The environment of a neutron star is that of an electrically conductive, highly magnetized, rotating sphere (the star). In the absence of high-energy radiative phenomena leading to the creation of electron positron pairs, these environments are structured by two opposing domes made up of particles of a given charge, and a belt surrounding the star made up of particles of opposite charge (see figure in Krause-Polstorff & Michel 1985).

These structures are known as electrospheres, due to their large charge differences. When the magnetic field has an axis of symmetry, and this is not aligned with the axis of rotation of the sphere/star, we speak of an oblique electrosphere. Simulations of aligned electrospheres were produced as early as 2000-2010. They are reviewed in (Cerutti & Beloborodov 2017). By contrast, simulations of oblique electrospheres are rare. To the best of my knowledge, only one article presents them, without giving any details (McDonald & Shearer 2009). I present simulations of oblique electrospheres produced very recently, with the aim of describing kinetic processes as accurately as possible, without making MHD or force-free field assumptions.

2 Method

These simulations are carried out using a specific code. It is governed by an algorithm combining aspects of particle-type codes (PIC), and Vlasov-type codes (with 3 dimensions in space, and one in momentum). Electromagnetic fields are calculated on a spherical grid, by decomposing the functions into spherical vector harmonics for the angular part, and Chebychev polynomials over a set of nested domains for the radial part. The implementation is similar to that of Pétri et al. (2002).

The relativistic motion of the particles is obtained by solving a relatively little-known relativistic equation, which I have re-demonstrated, adapted to very strong, moderate or zero magnetic fields. It is inspired from a method already used for the simulation of non-relativistic plasmas (Mottez et al. 1998; Mottez 2008). The rendering of motion in the case of strong magnetic fields is that of the particle guiding-center. The loss of particle energy caused by radiation associated with the curvature of their trajectory is taken into account, but the associated rate of high-energy photons is not calculated. As a result, we do not yet provide a radiation map of the electrosphere.

The choice of stationary solutions considerably speeds up calculations. A typical simulation takes less than an hour with a MPI run involving 3 processes on a Intel Core i7. There are no reduced sizes, a simulations can be run with realistic parameters.

As we like to give everything a name, I've named this code "Pulsar ARoMa" for *Pulsars' Asymmetric Rotating Magnetospheres*.

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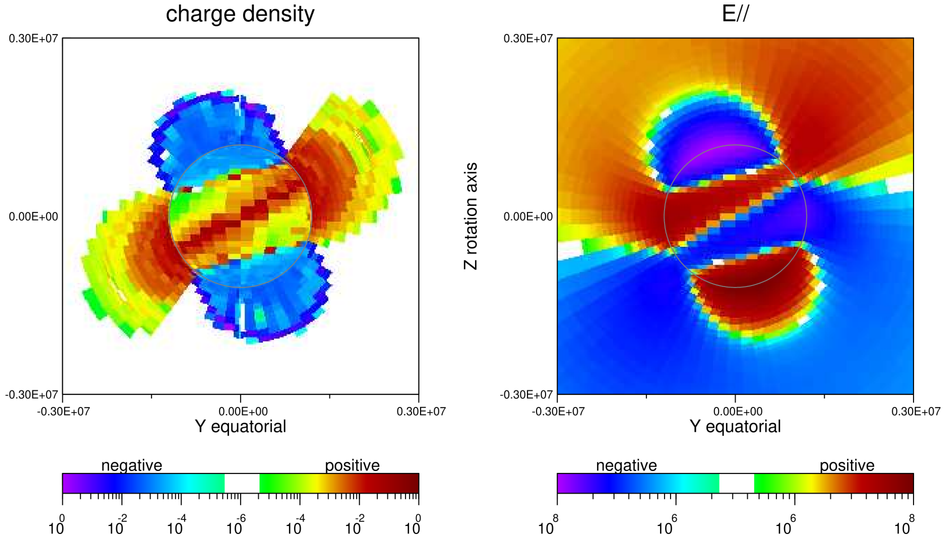

Fig. 1. Charge density and parallel electric field of an electrosphere. The figure shows the values at the star's surface (inside the circle that represents it), and in a meridian plane (outside this circle). Star radius: 12 km. Dipolar magnetic field, surface value: 10^9 G, rotation period: 10 ms. Rotation axis vertical. The magnetic axis is inclined 30 degrees to the rotation axis. Logarithmic scales in cold colors for negative values, in warm colors for positive values. System of units used: CGS.

3 First results

I have simulated electrospheres of neutron stars with a range of magnetic fields and rotation periods that is typical of millisecond pulsars, standard pulsars, and neutron stars beyond the "death line", i.e. neutron star that have not enough rotational energy to power a pulsar. I found that the electrospheric structure of oblique pulsars is similar to those of aligned pulsar. It is composed of two domes above the magnetic axis of symmetry, and a belt of opposite charge surrounding the magnetic equator. Nevertheless, their shape is influenced by the rotational effects: the domes and the belt are not symmetric relatively to the magnetic axis.

An example of an electrosphere with a plasma composed of electrons and protons is shown in fig. 1. We have seen that particle energies reach high values. Their Lorentz factors are shown in fig. 2. This suggests that for neutron stars in the regime of high rotational and magnetic energies, the electrons have sufficiently high energy to produce gamma rays via synchro-curvature radiation, and possibly electron-positron pairs (Voisin et al. 2018). A pulsar is therefore a potentially viable solution, as soon as radiation effects are included in the *Pulsar AroMa* code.

4 Outlook

When the particles in an electrosphere are energetic enough to emit gamma rays that generate pairs of electrons and positrons, the star's environment changes from electrosphere to pulsar magnetosphere (oblique or aligned). Ultimately, the aim is to adapt this code to pulsar simulation, with the inclusion of an explicit computation of high energy emissions, electron-positron pair creation, and general relativity effects.

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References

Cerutti, B. & Beloborodov, A. M. 2017, Space Sci. Rev., 207, 111
Krause-Polstorff, J. & Michel, F. C. 1985, A&A, 144, 72
McDonald, J. & Shearer, A. 2009, ApJ, 690, 13
Mottez, F. 2008, Journal of Computational Physics, 227, 3260
Mottez, F., Adam, J. C., & Heron, A. 1998, Computer Physics Communications, 113, 109

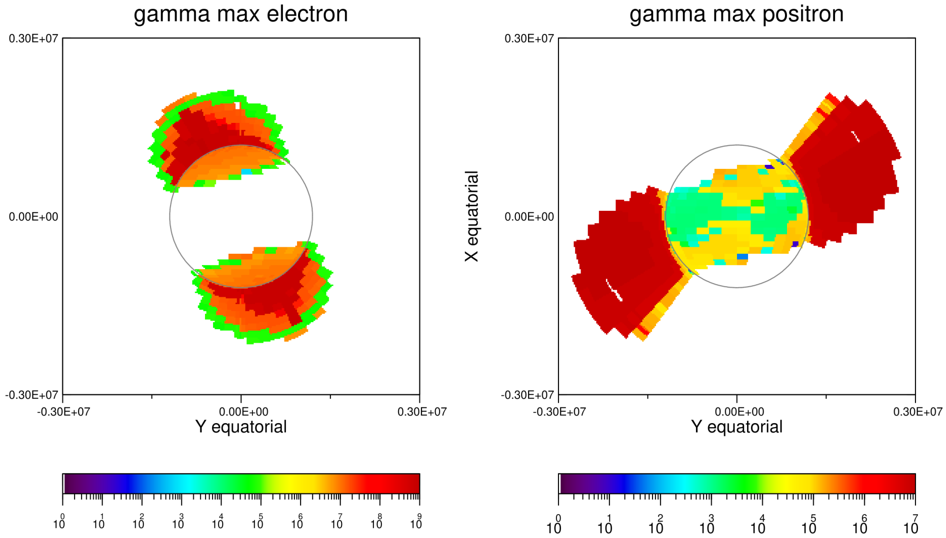

Fig. 2. Same simulation. Left: maximum Lorentz factor reached by electrons. Right, maximum Lorentz factor for positrons.

Pétri, J., Heyvaerts, J., & Bonazzola, S. 2002, A&A, 384, 414
Voisin, G., Mottez, F., & Bonazzola, S. 2018, MNRAS, 474, 1436