Structure and stability of pulsar's electrospheres

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We present a self-consistent model of the magnetosphere of an inactive, charged, aligned rotator pulsar with help on a semi-analytical and numerical algorithm. The only free parameter is the total charge of the system. This electrosphere is stable to vacuum breakdown by electron-positron pair production. However, it is unstable to the so-called diocotron instability which is an electrostatic instability. Eigenspectra and eigenfunctions for different disk models, which differ by the total charge of the disk-star system are presented. The evolution of this instability on a long time-scale is studied in the fully non-linear stage by means of numerical simulations. For multimode excitation, the average macroscopic response of the system can be described by a quasi-linear model. In the presence of an external source feeding the disk with positive charges, representing the effect of pair creation activity in the gaps, the diocotron instability gives rise to an efficient diffusion of charged particles across the magnetic field lines.

INTRODUCTION

A pulsar is a strongly magnetized rotating neutron star [1]. It emits electromagnetic radiation in a broad frequency range from radio waves to X- and γ-rays. Vacuum electric fields as high as 10^{12} V/m could develop at the surface of neutron stars. Fields of such strength can pull electric charges out of the neutron star's crust, even against the extraction work opposed by inter- and intra-ionic forces [2]. As a result, charged particles freely expand in the star's close environment forming a space charge filled atmosphere which we refer to as an electrosphere [3].

Understanding pulsar's periodic high and low energy emissions involves a quantitative and self-consistent description of the structure and dynamics of this electrosphere. Most models presently considered assume the closed part of the magnetosphere of the pulsar to be entirely filled with charged plasma in corotation with the star. This may however not be so. We have revisited the structure of the electrosphere of aligned rotators and have shown that even their closed magnetosphere is not completely plasma-filled, but rather that oppositely charged polar and equatorial regions separated by large vacuum gaps form. As a result, the equatorial region is in differential over-rotation as compared to the star.

STATIC ELECTROSPHERE [4]

We have developed a numerical algorithm to construct several models of pulsar's electrosphere. This scheme progressively transfers charges from the surface of the rotating neutron star to its electrosphere. An example is shown in the Fig. 1.

$\boxed{\text{Total charge of the system } Q \equiv \text{only free parameter of the model}}$

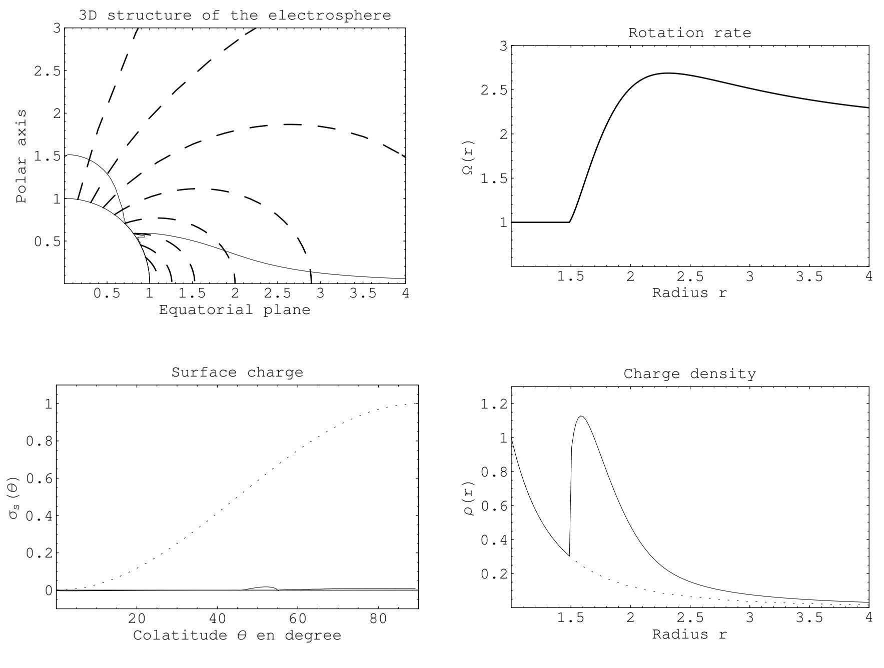

Figure 1: Structure of a pulsar electrosphere. From left to right and top to bottom, the geometry of the electrosphere, the differential rotation rate in the equatorial plane, the final charge density at the surface and the differential charge density in the disk.

Main properties

The star is entirely surrounded by charge-separated plasma consisting of

- an equatorial belt (red), positively charged
- two negatively charged domes (green) located over the polar caps.

The two charged regions are separated by large vacuum gaps :

- inner part of the equatorial belt corotating with the star, because no gap
- outer part is super-rotating everywhere
- differential Goldreich-Julian charge density sharply peaked at the innermost part of the disk
- residual stellar charge left on the star's surface less than 1% of the initial surface charge.

DIOCOTRON INSTABILITY

1. Linear analysis [5]

We studied the consequences of this electrospheric structure on the motion of charged particles in the star's dipolar magnetic field. The differential over-rotation of the equatorial charged disk generates electric current flow in the electrosphere and destabilise the particle trajectories.

By a linear perturbation analysis

⇒ unstable azimuthal modes m exist

⇒ determination of the eigenfrequencies (Ω_p) and growth rates (γ), Fig. 2.

Stability properties as a function of the total charge Q:

- the smaller the total charge, the faster the growth of instabilities
- when the total charge increases, the growth rates decrease
- nevertheless the instability persists.

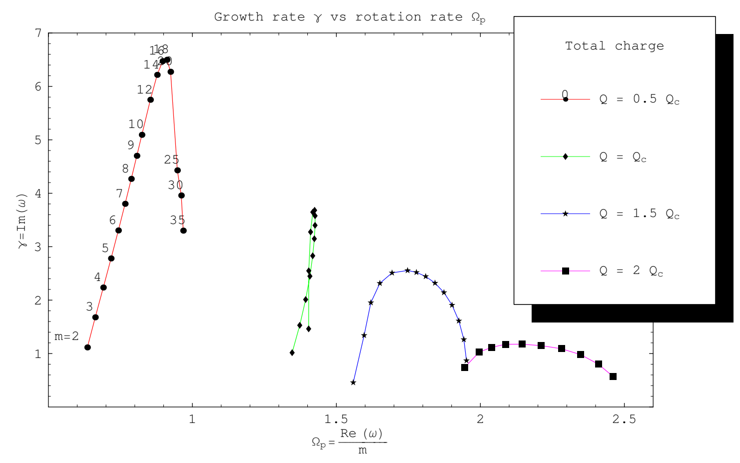

Figure 2: Eigenvalues of the diocotron instability in the plane (Ω_p, γ). Q_c is the central point charge located inside the neutron star.

2. Non-linear evolution [6]

Linear approach insufficient to assess the long term behavior of the system

⇒ non-linear saturation of unstable modes studied by way of numerical simulations

⇒ take full account of these non-linearities.

If no external source of charge, the charge distribution evolves rapidly towards the formation of a few strong charge condensations which orbit the star at high speed. The disk evolves into a few super-particles propagating like solitons, Fig. 3!

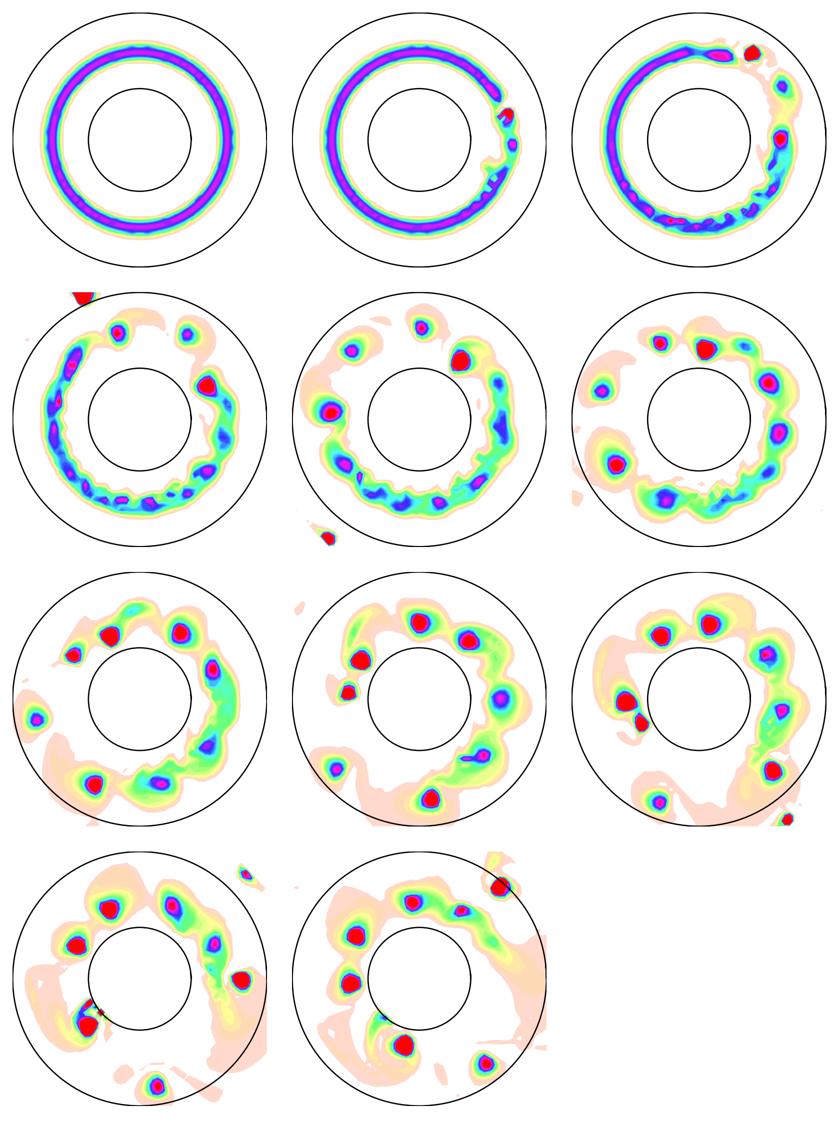

Figure 3: Non-linear evolution of the diocotron instability in an infinitely thin disk.

We also considered the possibility that charged particles be continuously supplied to the disk by $e^\pm$ pair avalanches induced close to the neutron star by high-energy photons traveling in the vacuum gaps ⇒ entirely different evolution :

- instability develops into relatively smaller scale electrostatic turbulence
- electric fluctuations induce a net equatorial charge flux, i.e. an electric current, leaving the pulsar's environment
- main effect of the instability is to make it possible for charged particles to diffuse across the field lines.

2. Quasi-linear model

We have also developed a quasi-linear model of the diocotron instability. Quasi-linear theory is justified when many azimuthal modes are excited.

Approximation :

- follow the azimuthally averaged part of the disk's charge distribution
- neglect bilinear mode coupling terms in the evolution of non axisymmetric modes.

In the quasi-linear framework, system's evolution ≡ analysis of the rate of linear growth for the charge density profile, at any given time.

Consequences :

- azimuthally averaged charge density evolves due to diffusion in the associated electrostatic non-axisymmetric perturbations
- growth rates of these fluctuations are time dependent
- tend to evolve to marginal stability
- However, due to charge injection in the disk, it is never strictly reached and a stationary diffusive charge flux appears instead.

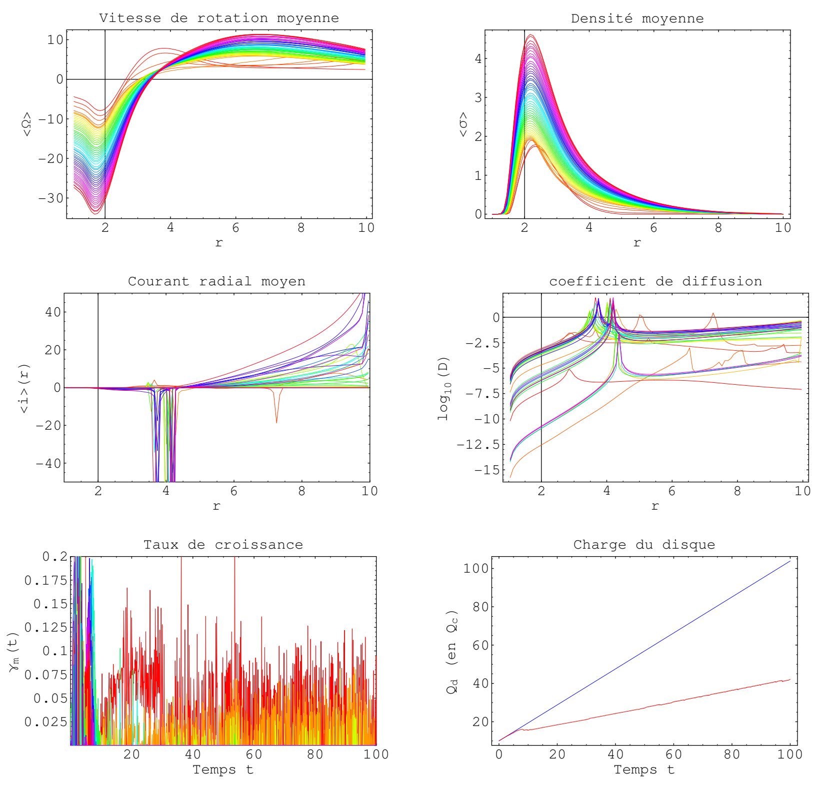

Figure 4: Quasi-linear evolution of the diocotron instability with an additional external source. From left to right and top to bottom, angular velocity, mean charge density, electric current, diffusion coefficient, evolution of growth rate and charge in the disk.

$e^\pm$ PAIR CREATION [4]

1. Photon-magnetic field interaction

When the stellar magnetic field strength becomes comparable to the critical magnetic field given by $B_c = m_e^2 c^2 / e\,\hbar \approx 4.4 \cdot 10^9$ T, photon disintegration occurs following the process :

$$\gamma + B \rightarrow e^+ + e^-$$

For typical pulsars with magnetic field strength of $B_* = 10^8$ T and period $P = 1$ s, the breakdown region is limited to $\approx 50\,R_* \ll R_L \approx 4800\,R_*$.

⇒ curvature photon conversion into $e^\pm$ on the magnetic field is not an efficient mechanism to break the vacuum gaps which appear in our solutions.

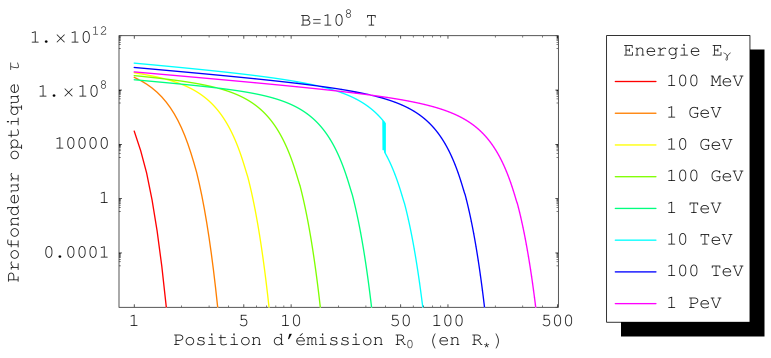

Figure 5: Optical depth for $\gamma - B$ interaction as a function of photon energy and emission position R_0.

2. Photon-photon interaction

The two-photon pair production is generally considered in outer gap models as a trigger for $e^\pm$ cascade. Curvature gamma rays emitted by accelerated particles interact with the thermal X-ray photons from the polar caps due to the process :

$$\gamma + \gamma \rightarrow e^+ + e^-$$

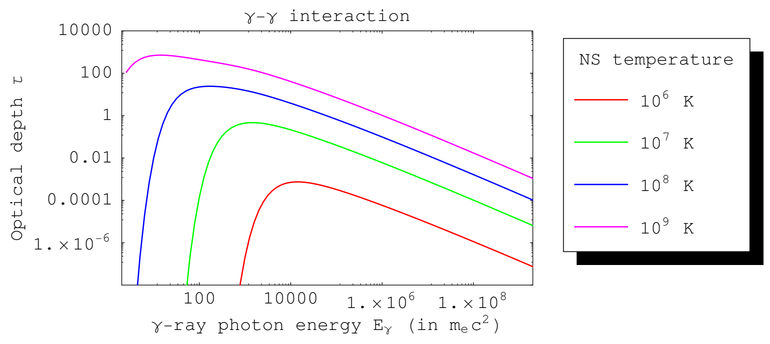

Figure 6: Optical depth for $\gamma - \gamma$ interaction as a function of the gamma-ray energy E_γ and neutron star surface temperature T.

For usual surface temperatures (less than 10^7 K), the process of lepton pair creation by $\gamma - \gamma$ collisions is dominated by the $\gamma - B$ interaction very near the neutron star.

CONCLUSION

Electrodynamically self-consistent solutions to the magnetospheric structure exist. They are called electrospheres. In the case of an aligned rotator, their properties are :

- finite in extent and in a self-consistent electrostatic equilibrium ;
- large vacuum gaps separate the corotating negatively charged polar regions from a differentially rotating positive belt ;
- the vacuum breakdown of these large gaps by $e^\pm$ pair creation is not efficient enough to cause the filling-up of the whole magnetosphere up to the light surface ;
- the equatorial charge-separated disk is linearly unstable to the diocotron instability. It operates on very short time scales, of the order of a few neutron star rotation periods ;
- on a large time-scale, the instability redistributes the electric charge over the disk. The system approaches marginal stability ;
- in some cases, a permanent outwardly oriented electric current is observed to form in the equatorial plane, carrying away a large fraction of the charge brought by an external source of charges.

Current circulation is a possibly new solution to the problem of the current closure in the electric circuit of an active pulsar magnetosphere.

Perspectives :

- loss of charge through the equatorial disk should be accompanied by the development of a negatively charged wind escaping from the poles
- the current system should be globally closed
- electrosphere should then reach a stationary state
- still with large vacuum gaps under considerable potential drop, partially active to pair avalanching.

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