Dissipative Pulsar Magnetospheres

C. Kalapotharakos[1,2], D. Kazanas[1], A. K. Harding[1], I. Contopoulos[3]

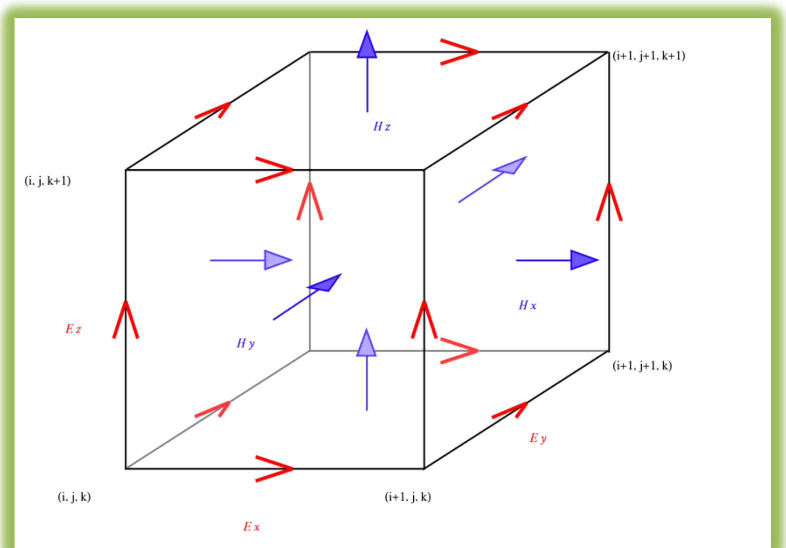
[1]Astrophysics Science Division, NASA/Goddard Space Flight Center, Greenbelt, MD 20771, USA
[2]University of Maryland, College Park UMDCP/CRESST), College Park, MD 20742, USA
[3]Research Center for Astronomy, Academy of Athens, Athens 11527, Greece

Abstract

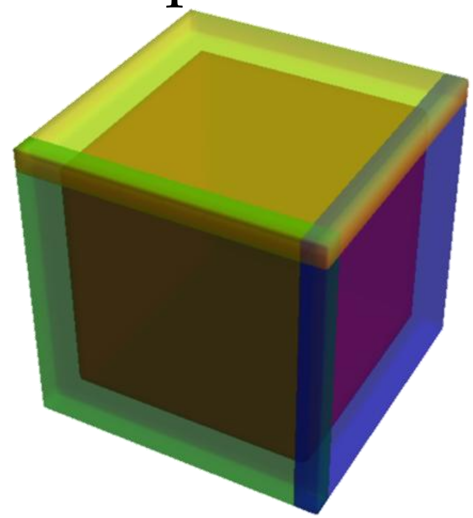
We present the magnetic and electric field structures as well as the **currents** and **charge densities** of pulsar magnetospheres which do not obey the ideal condition, $\mathbf{E}\cdot\mathbf{B}=\mathbf{0}$. Since the **acceleration** of particles and the production of radiation requires the presence of an electric field component parallel to the magnetic field, $\mathbf{E}_{\parallel}$ the structure of non-Ideal pulsar magnetospheres is intimately related to the production of **pulsar radiation**. Therefore, knowledge of the structure of non-Ideal pulsar magnetospheres is important because their **comparison** (including models for the production of radiation) with observations (**see poster by Alice K. Harding**) will delineate the physics and the parameters underlying the **pulsar radiation** problem. We implement a variety of prescriptions that support nonzero values for $\mathbf{E}_{\parallel}$ and explore their effects on the structure of the resulting magnetospheres. We produce families of solutions that span the entire range between the V**acuum Retarded Dipole (VRD)** and the (ideal) **Force-Free Electrodynamic (FFE)** solutions. We also compute the amount of **dissipation** as a fraction of the Poynting flux for pulsars of different angles between the rotation and magnetic axes and conclude that this is at most 20-40% (depending on the non-ideal prescription) in the aligned rotator and 10% in the perpendicular one. We present also the limiting solutions with the property $J=\rho c$ and discuss their possible **implication** on the determination of the "on/off" states of the **intermittent** pulsars. Finally, we find that solutions with values of J greater than those needed to null $\mathbf{E}_{\parallel}$ locally produce **oscillations**, potentially observable in the data.

The Code

- We use a time dependent Finite Difference Time Domain (FDTD) code in order to evolve our systems in time.
- We have implemented the Perfectly Matched Layer (PML) technique which is an absorbing and non reflecting outer boundary. This allows us to follow the magnetosphere for many rotations (Kalapotharakos & Contopoulos 2009).



FDTD 3D scheme



Perfectly Matched Layer (PML)
Absorbing and non-reflecting outer layers
Kalapotharakos & Contopoulos (2009)

Ideal Force-Free (FFE) Solutions

We solve the time-dependent Maxwell equations

$$\frac{\partial E}{\partial t} = \nabla \times B - 4\pi J \qquad \nabla \cdot B = 0$$

$$\frac{\partial B}{\partial t} = -\nabla \times E \qquad \nabla \cdot E = \frac{1}{4\pi}\rho_e$$

considering the Ideal Force-Free conditions

$$E \cdot B = 0$$

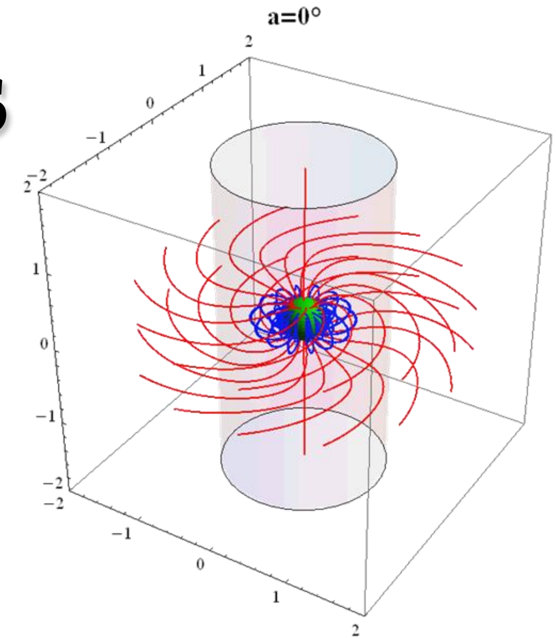
$$\rho_e E + J \times B = 0$$

In this case we have the following expression for the current

$$J = \rho_e \frac{E \times B}{B^2} + \frac{1}{4\pi}\frac{\left(B \cdot \nabla \times B - E \cdot \nabla \times E\right)}{B^2} B \quad \text{(Gruzinov1999)}$$

The first FFE solution for the aligned rotator presented by Contopoulos et al. 1999 and for the oblique rotators by Spitkovsky 2006.

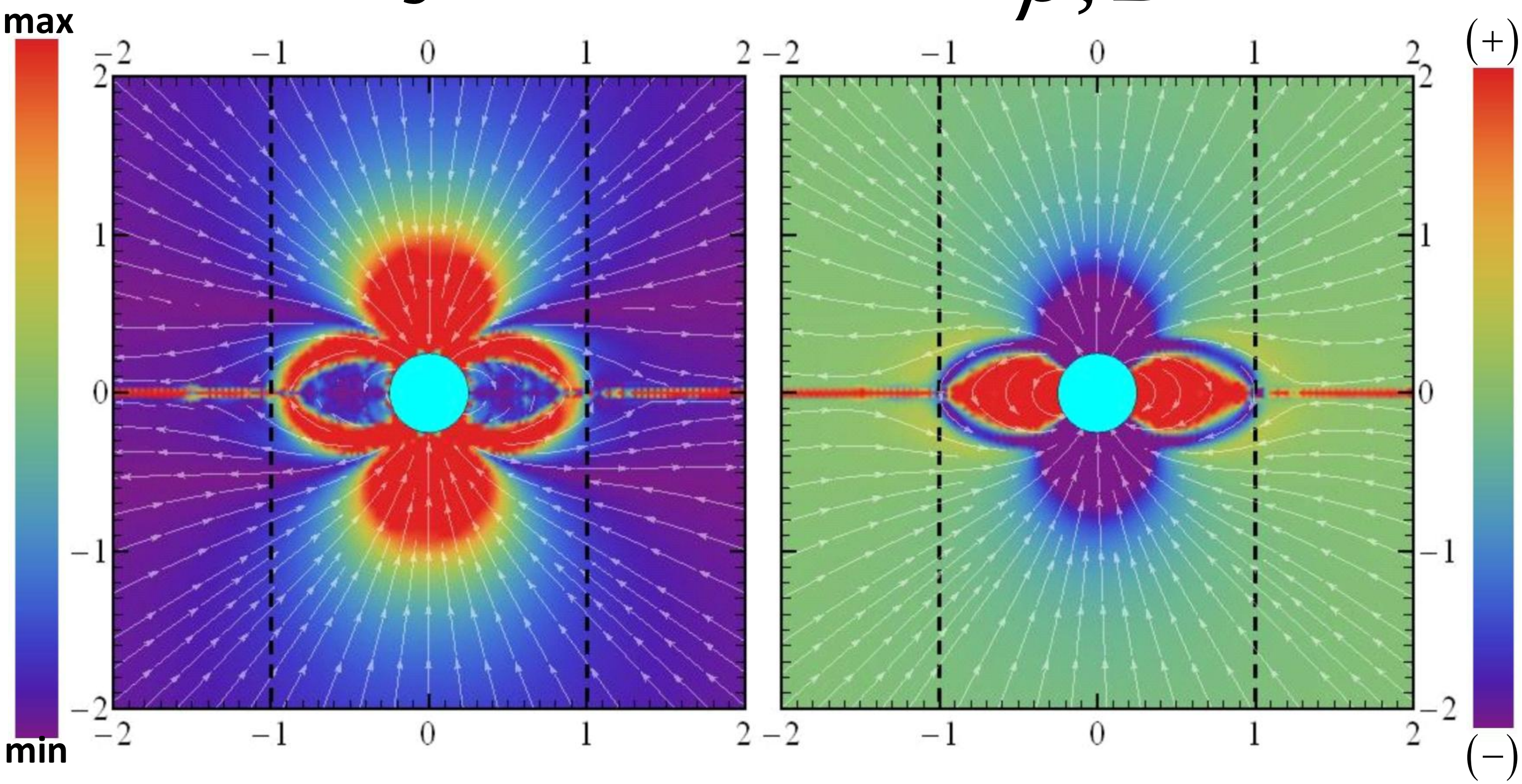
(FFE) solutions



$$\alpha = 0^\circ$$

The structure of the poloidal current J, poloidal magnetic field B and the charge density ρ on the poloidal plane (μ, Ω) for the FFE solutions and for α=0°.

J ρ, B

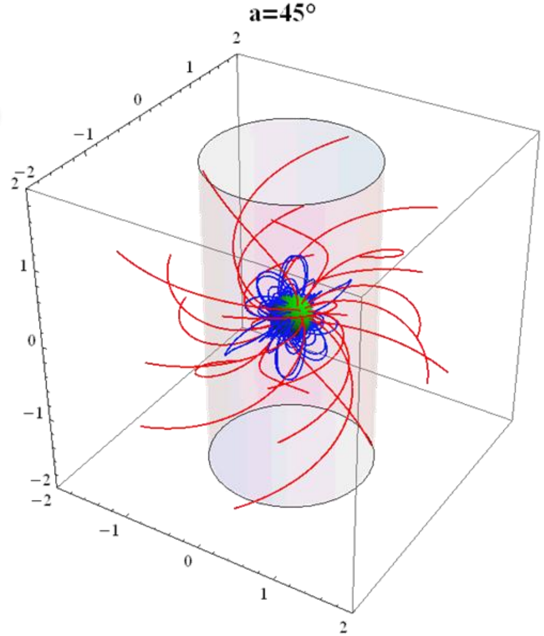


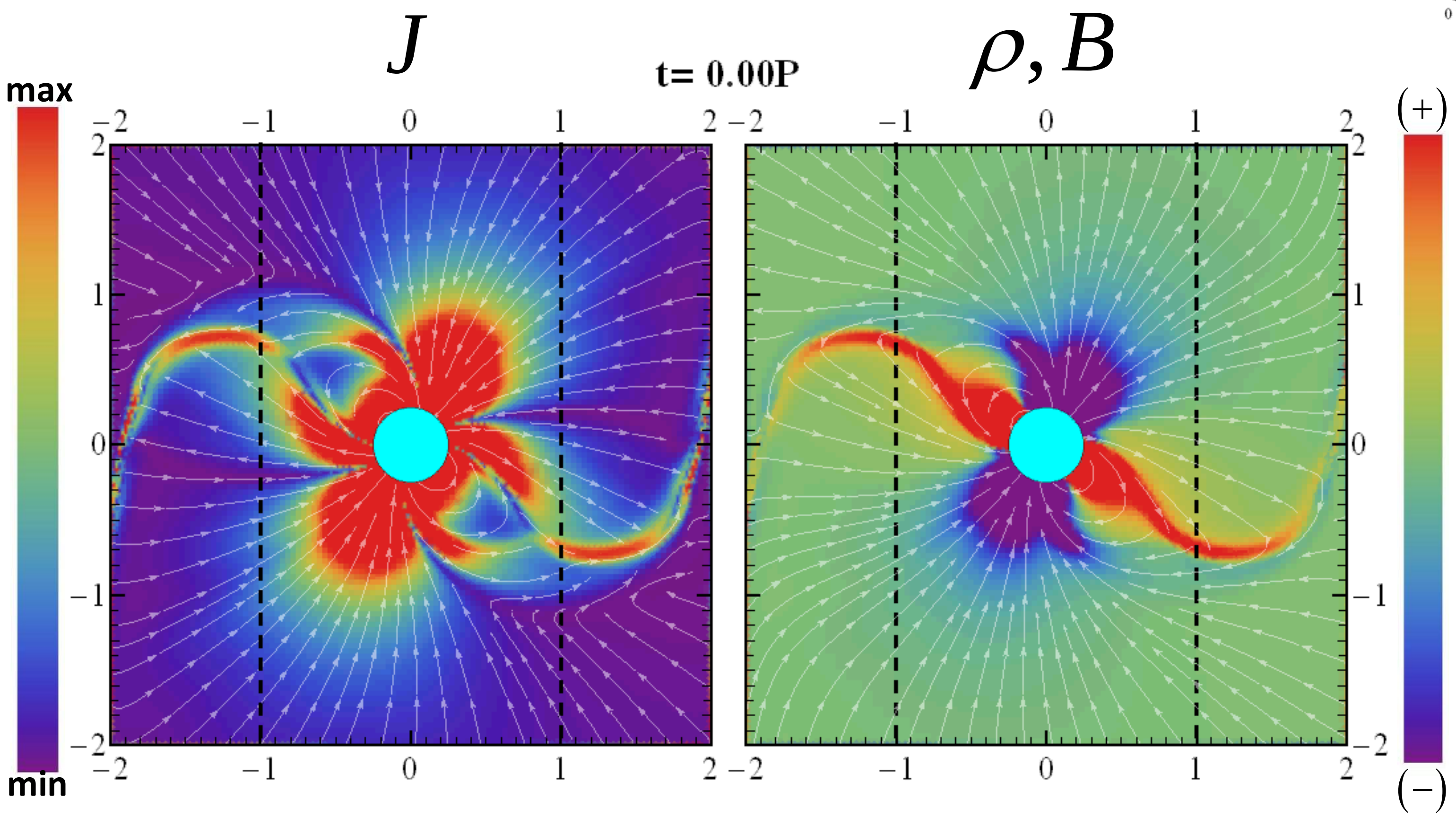
The corresponding 3D structure of the magnetic field lines.

(FFE) solutions

$$\alpha = 45^\circ$$

The structure of the poloidal current J, poloidal magnetic field B and the charge density ρ on the poloidal plane (μ, Ω) for the FFE solutions and for $\alpha=45^\circ$.



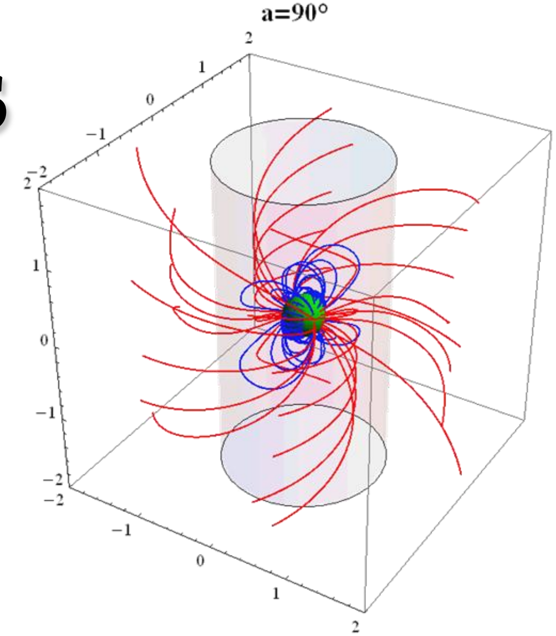


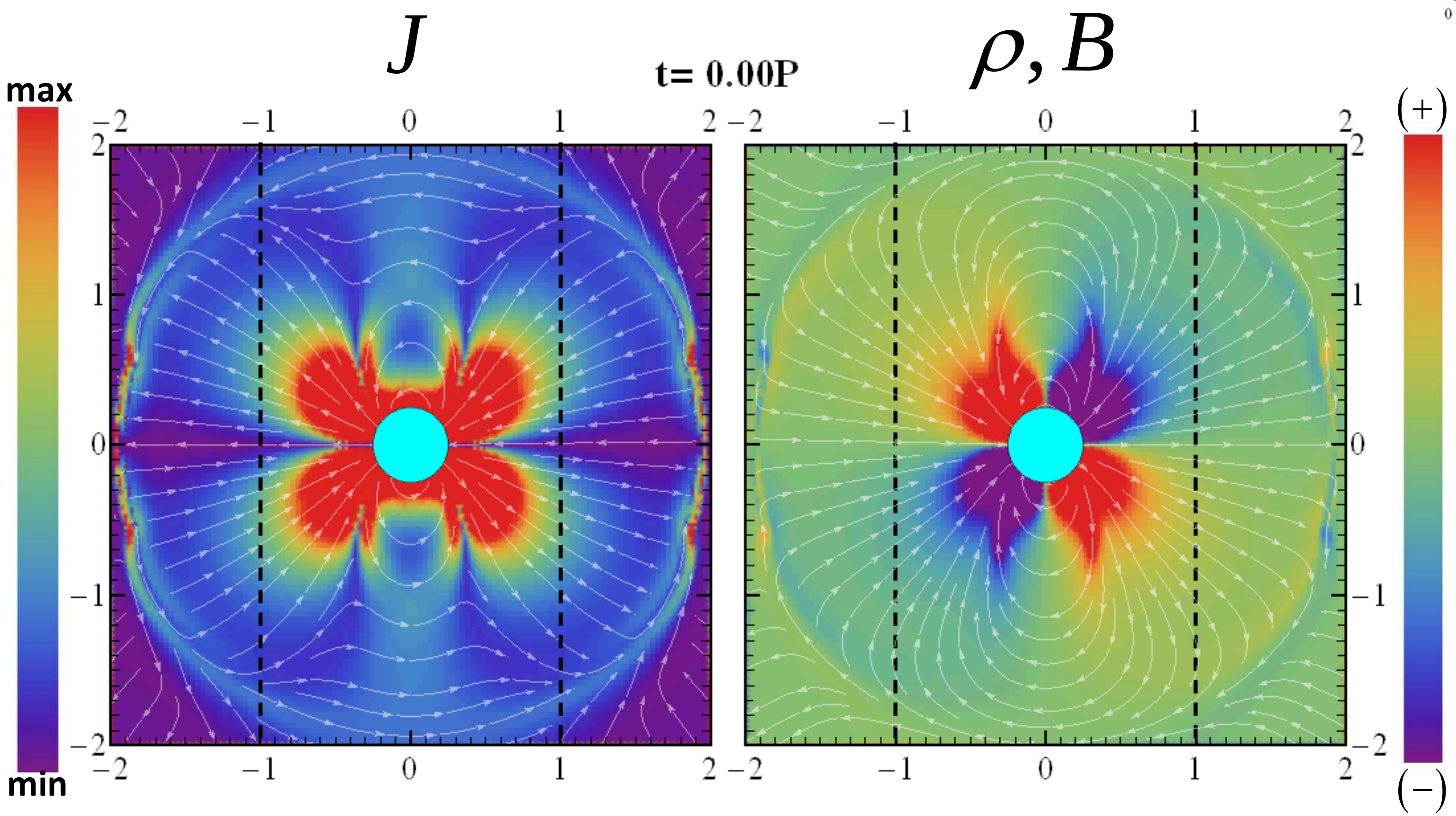
The corresponding 3D structure of the magnetic field lines.

(FFE) solutions

$\alpha = 90^\circ$

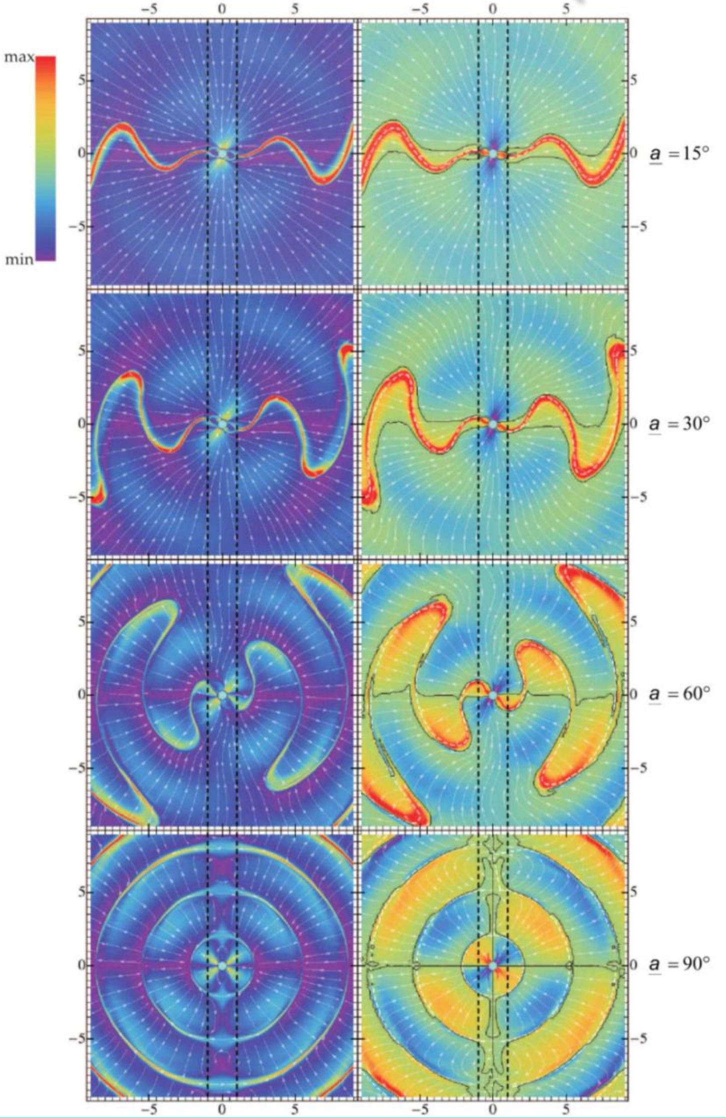
The structure of the poloidal current J, poloidal magnetic field B and the charge density ρ on the poloidal plane (μ, Ω) for the FFE solutions and for α=90°.

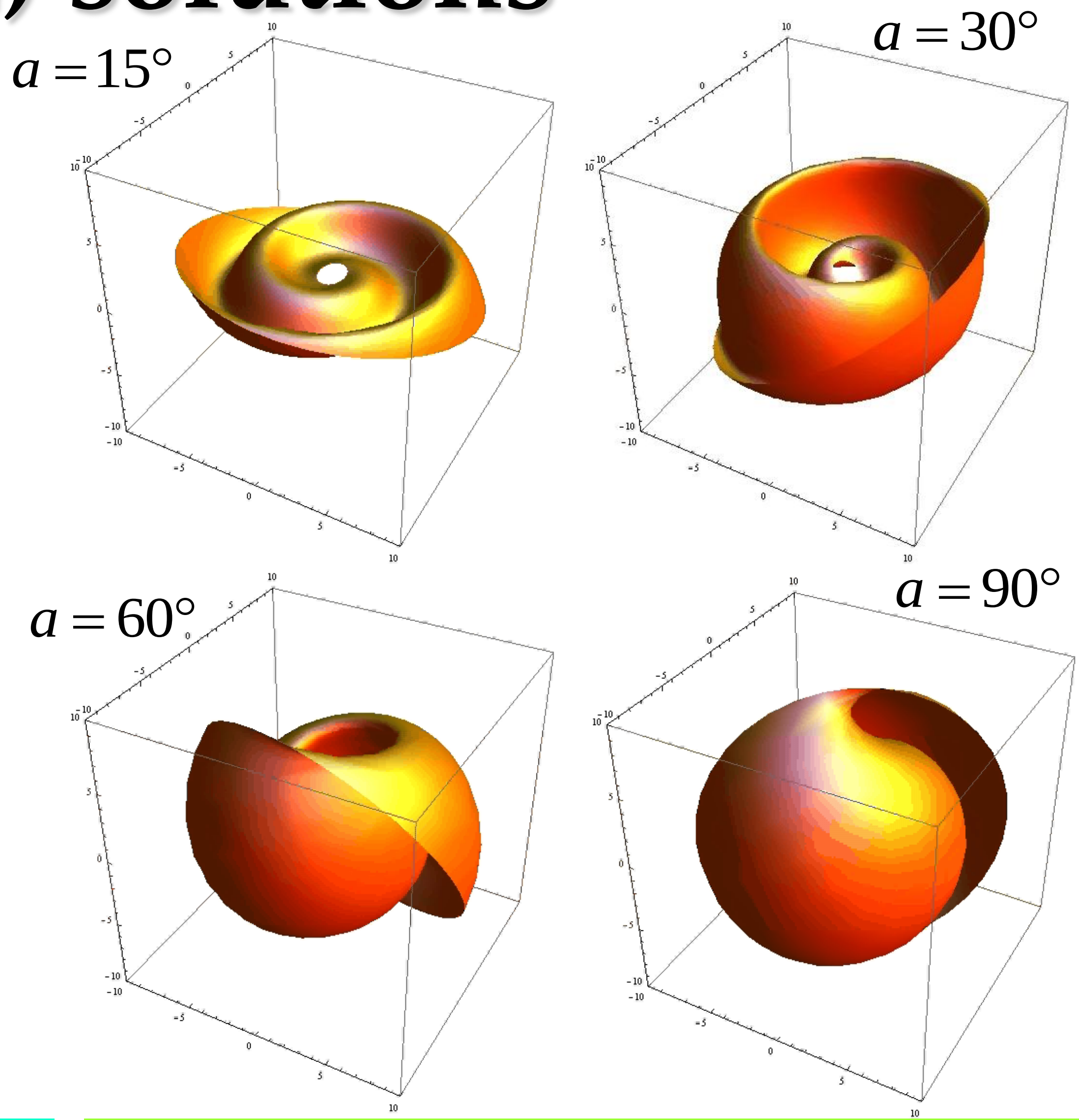




The corresponding 3D structure of the magnetic field lines.

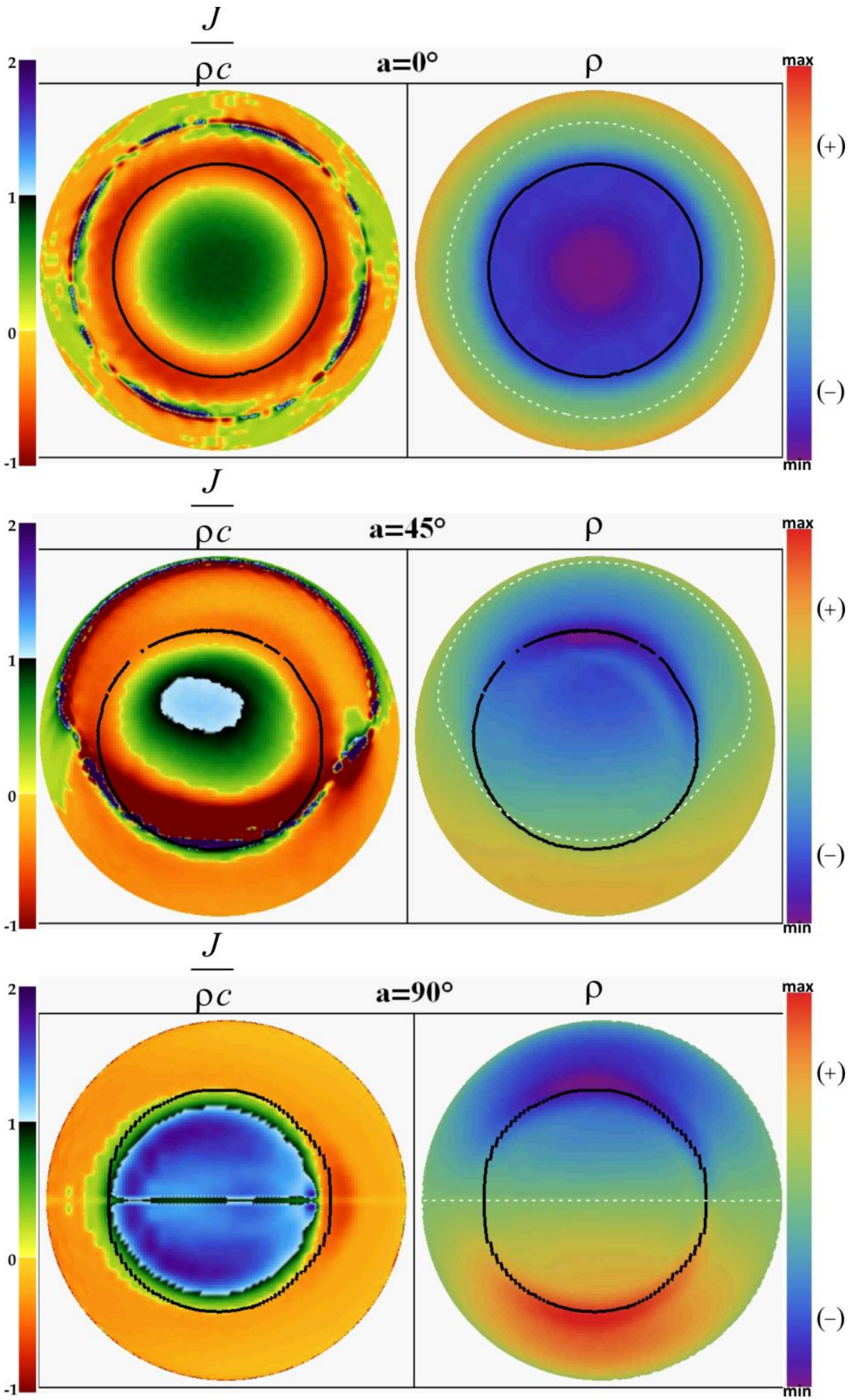
(FFE) solutions





The structure of the FFE magnetospheres up to 10 times the Light Cylinder radii (Kalapotharakos et al. 2012a)

The 3D structure of the equatorial current sheet of the FFE solutions approaches the kinematic split monopole solution of Bogovalov 1999



(FFE) solutions

Polar Cap

The distribution of the values J/ϱc and ϱ on the polar cap. The black line denotes the polar cap rim inside which we have the open magnetic field lines. The white dashed line denotes the zero charge line.

There is a very complex structure especially for the intermediate α values. We see time-like currents (J<ϱc), space-like currents (J>ϱc) (counter streaming flows of different kind of charges are required) and negative currents (the local excess of the charge density flows inwards).

This complex structure rises some questions about the efficiency of the microphysical mechanisms to support them adequately.

The Problem

Vacuum

- $\rho=0$
- $E_{\parallel}\neq0$

FFE

- $\rho\neq0$
- $E_{\parallel}=0$

None of these two limiting solutions (Vacuum, FFE) can be observed. In the Vacuum solutions we don't have particles while in the FFE solutions we don't have the electric fields necessary for the particle acceleration.

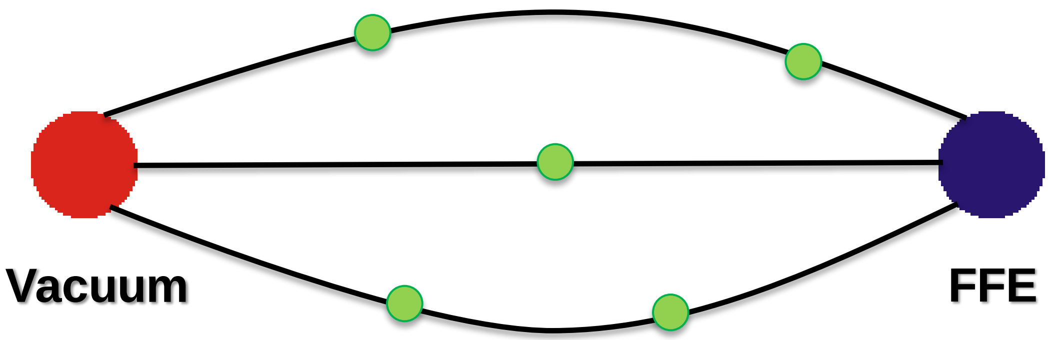
Additional problems

a) Intermittent Pulsars
b) Breaking Index

} They are consistent neither to Vacuum nor FFE

So we need dissipative solutions

The Problem



In the phase space of solutions the **Vacuum** and the **FFE** solutions are limiting cases. However, there is an infinite number of paths that these limiting cases can be connected. Along which path and at which point of the path a Pulsar lies is what determines its properties.

Dissipative Solutions

In order to produce dissipative solutions we use a prescription for the current density J that reads

$$\mathbf{J} = c\rho\frac{\mathbf{E}\times\mathbf{B}}{B^2} + \sigma\mathbf{E}_{||}$$

(Kalapotharakos et al. 2012b)

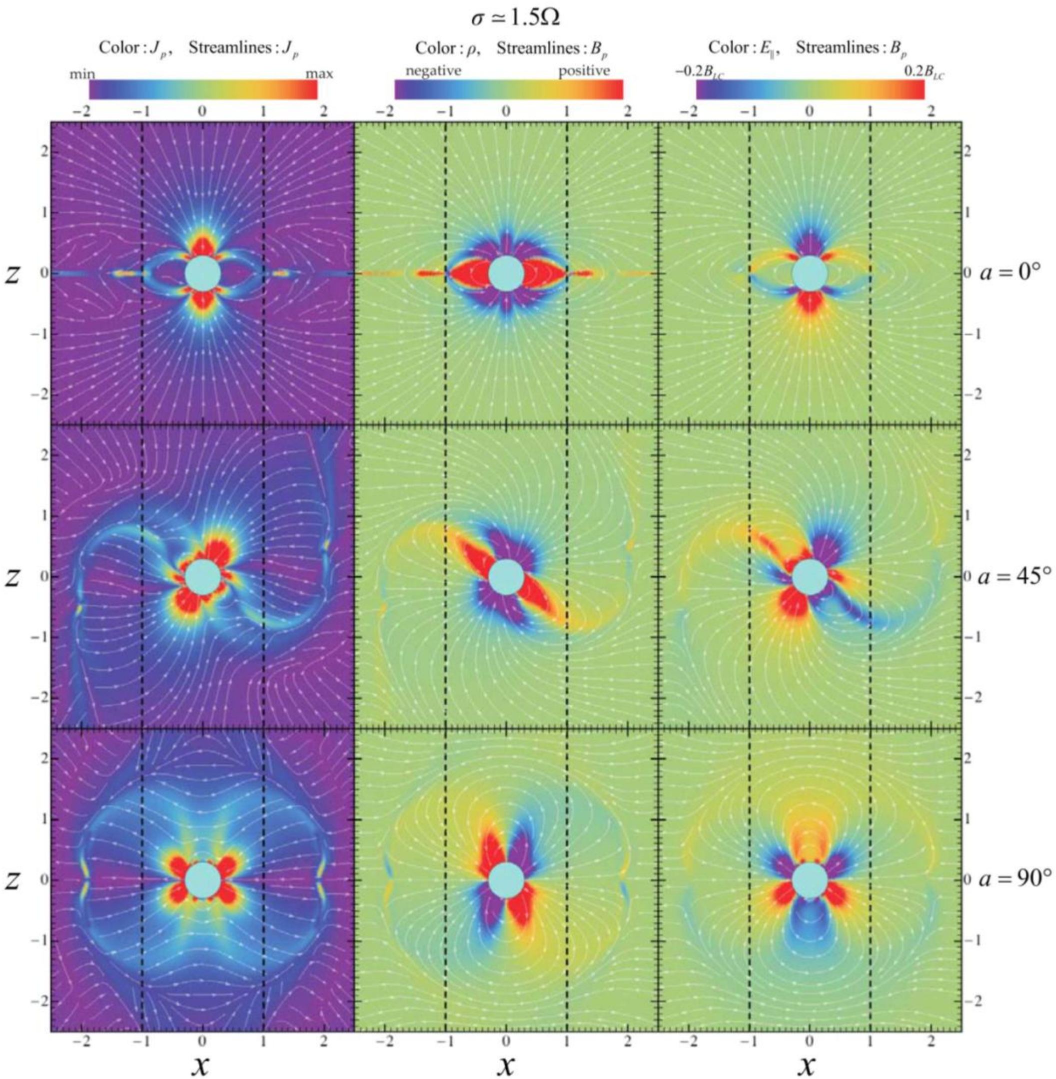
This very simplistic expression produces an entire spectrum of solutions from Vacuum (for $\sigma\rightarrow 0$) to FFE (for $\sigma\rightarrow\infty$)

σ: 0 ⟶ ∞

Vacuum ⟶ **FFE**

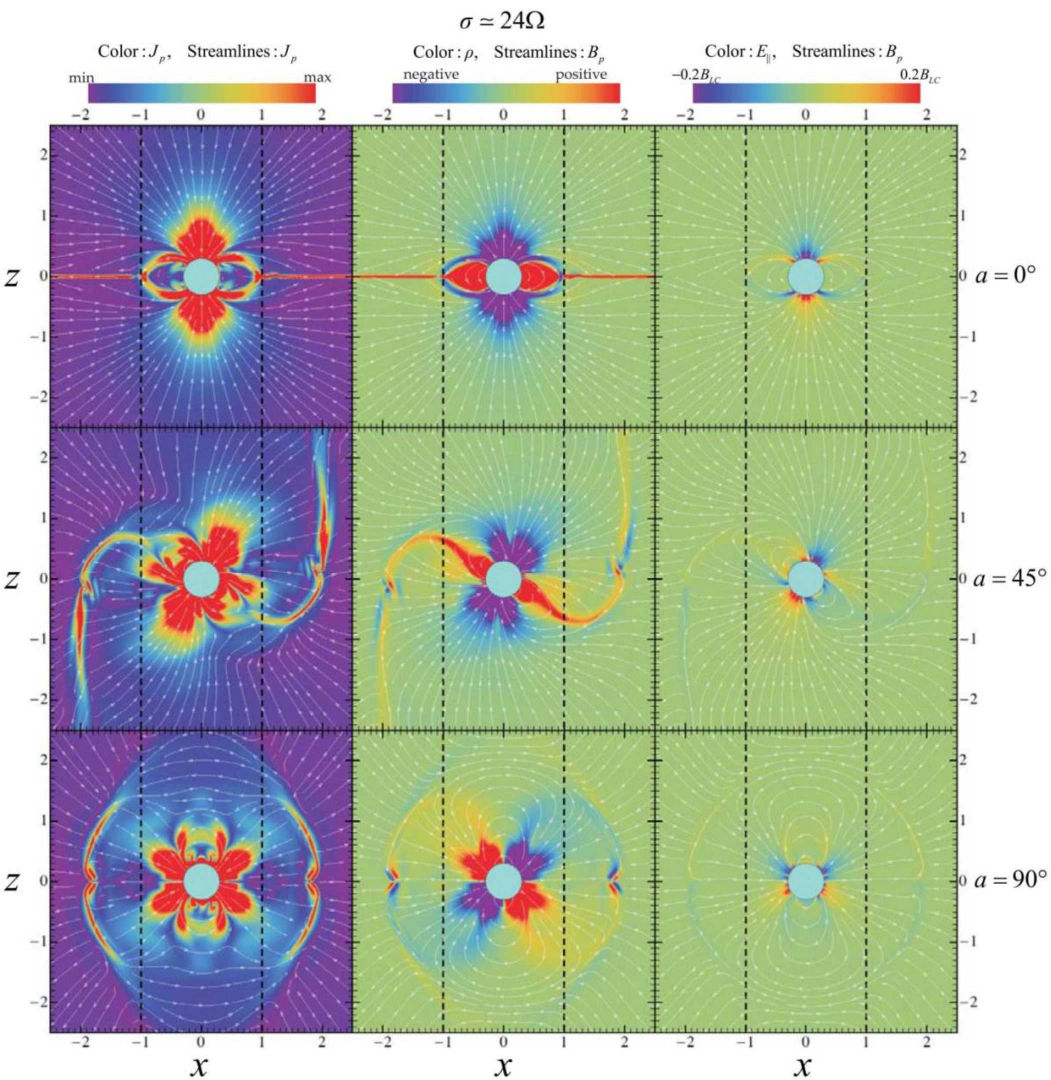
Similar dissipative solutions could be produced using different prescriptions for the current density (Gruzinov 2007, 2008; Li et al. 2012; Kalapotharakos et al. 2012b)

Dissipative Solutions



Non-ideal magnetospheric solutions in the poloidal plane (μ,Ω) for a small σ value (σ = 1.5Ω). The left-hand column shows the poloidal current modulus (in color scale) together with the streamlines of the poloidal current. The middle column shows the charge density (in color scale) together with the field lines of the poloidal magnetic field. The right-hand column shows the parallel electric field component E (in color scale) together with the lines of the poloidal magnetic field. The color ranges purple-green and green-red indicate antiparallel and parallel directions of E (relative to the magnetic field), respectively.

Dissipative Solutions



Non-ideal magnetospheric solutions in the poloidal plane (μ,Ω) for a high σ value (σ = 24Ω).

The structure shown in the first two columns is quite similar to that of the FFE solutions (the main difference from the FFE solution can be seen in the distribution of the parallel electric component third column).

Dissipative Solutions

Spin Down Rate

$$L = \begin{cases} \frac{2}{3}\frac{\mu^2\Omega^4}{c^3}\sin^2 a & \text{Vacuum} \\ \frac{\mu^2\Omega^4}{c^3}(1+\sin^2 a) & \text{FFE} \end{cases}$$

$L(0^\circ) = 0$ (Vacuum)
$L(90^\circ) = \frac{2}{3}$ (Vacuum) (Deutsch 1955)

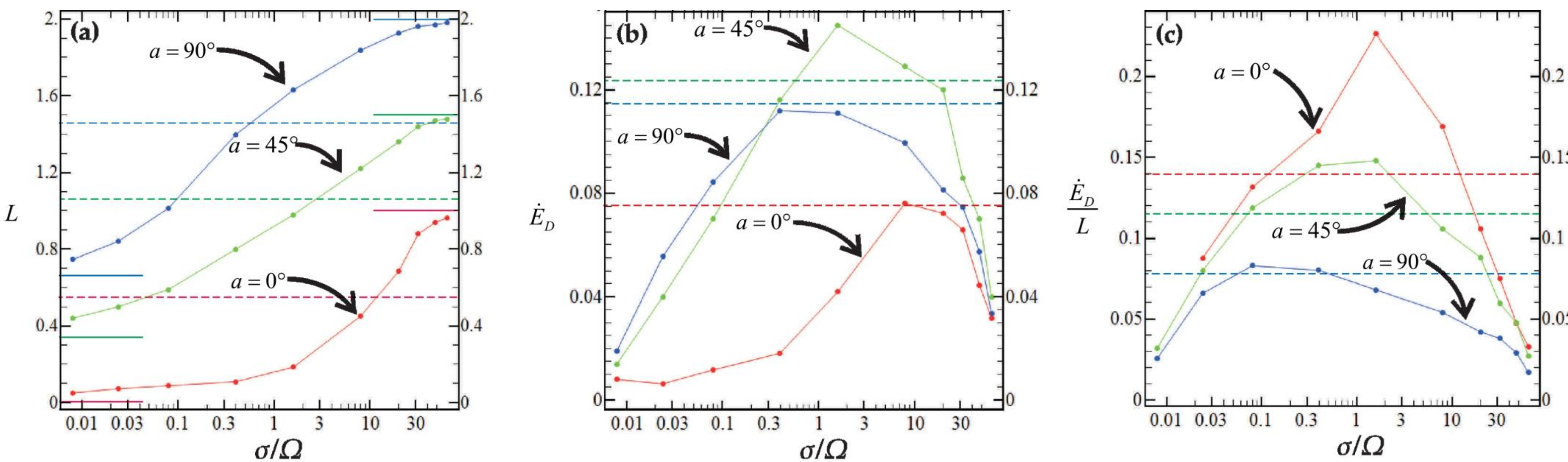
$L(0^\circ) = 1$ (FFE)
$L(90^\circ) = 2$ (FFE) (Spitkovsky 2006)

Dissipation Power

$$\dot{E}_D = \int_{r_1<r<r_2} \mathbf{J}\cdot\mathbf{E}\, dV$$

Vacuum $\dot{E}_D = 0$

FFE $\dot{E}_D = 0$



The Poynting fluxes L (measured on the surface of the star) as a function of σ . The horizontal solid line elements denote the L values corresponding to the Vacuum and the FFE solutions. (b) The dissipation energy rate $\dot{E}_D$ as a function of σ. (c) The fraction $\dot{E}_D / L$ never exceeds the values 10%–20%, while for σ → 0 and σ → ∞ it goes toward 0. The dashed horizontal lines in all three panels denote the values corresponding to simulations with J/ρc = 1 (see below).

Dissipative Solutions J=ρc

Charges accelerate to c.

It seems reasonable to consider $J \approx \rho c$

These solutions discriminate between magnetospheres consistent with only a single sign charge carrier $J < \rho c$ and those that require carriers of both signs of charges.

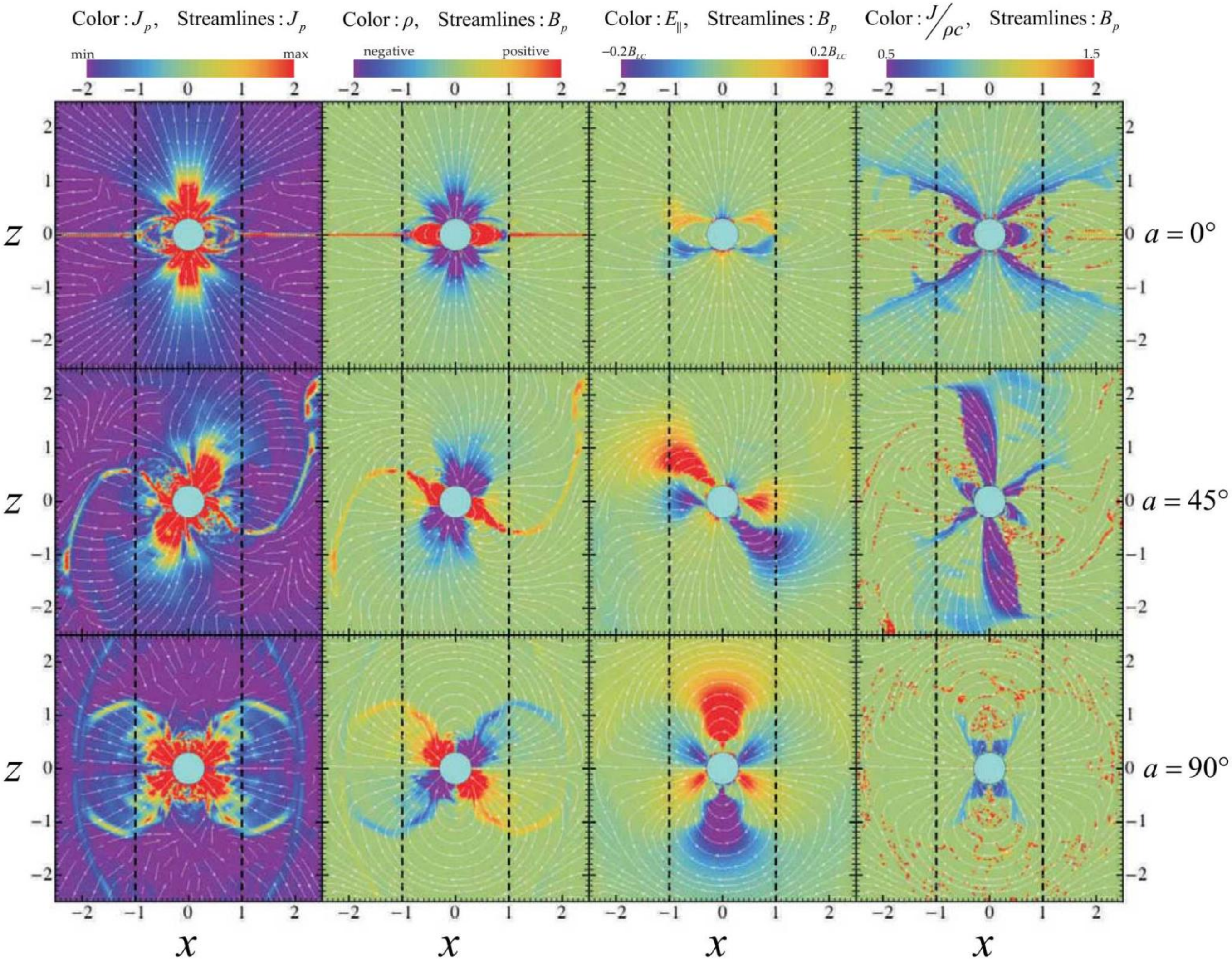
Space-like $(J > \rho c)$ flows require points of pair production.

Microphysical studies (Harding & Muslimov 2001) of the polar cap physics have shown steady-state models are compatible with $J \approx \rho c$.

Beloborodov (2008), Timokhin & Arons (2012) demonstrated that no discharge occurs if $J/\rho c < 1$ and that the $E_{||}$ and the discharge generated when $J/\rho c > 1$ or $J/\rho c < 0$ are time-dependent.

Dissipative Solutions J=ρc

Using the prescription $\mathbf{J} = c\rho\frac{\mathbf{E}\times\mathbf{B}}{B^2} + \sigma\mathbf{E}_{||}$ we locally vary σ so that $J=\rho c$.

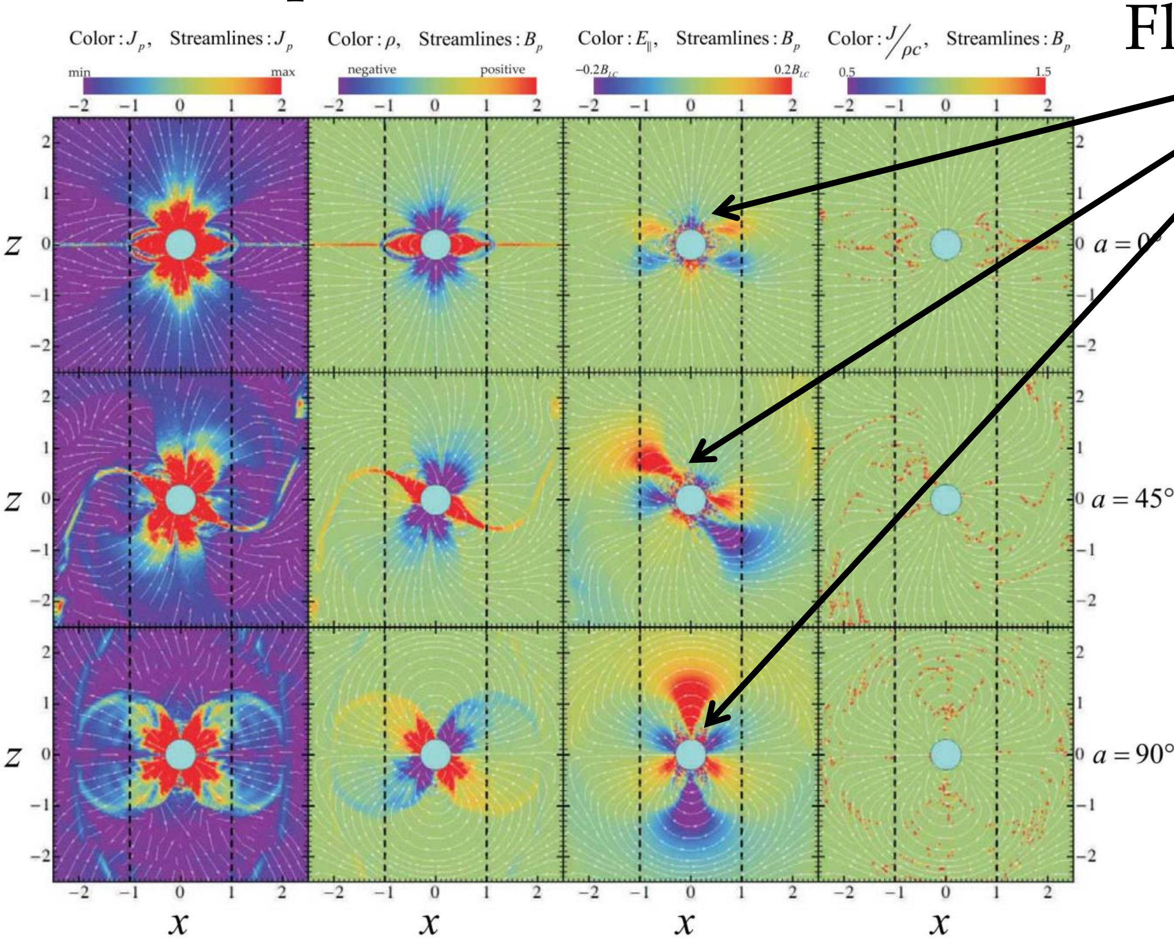


In time-like regions (J<ρc) for $\sigma\to\infty$, $E_{||}\to 0$ in such a way that their product is equal to that indicated by the FFE prescription.

Dissipative Solutions J=ρc

A more general expression for **J** $\mathbf{J} = c\rho\frac{\mathbf{E}\times\mathbf{B}}{B^2} + f\mathbf{B}, \quad (f : J = \rho c)$ not related to E‖ can produce J/ρc=1 everywhere but only at the expense of fluctuations.

Fluctuations of $\mathbf{E}_{\parallel}$ direction



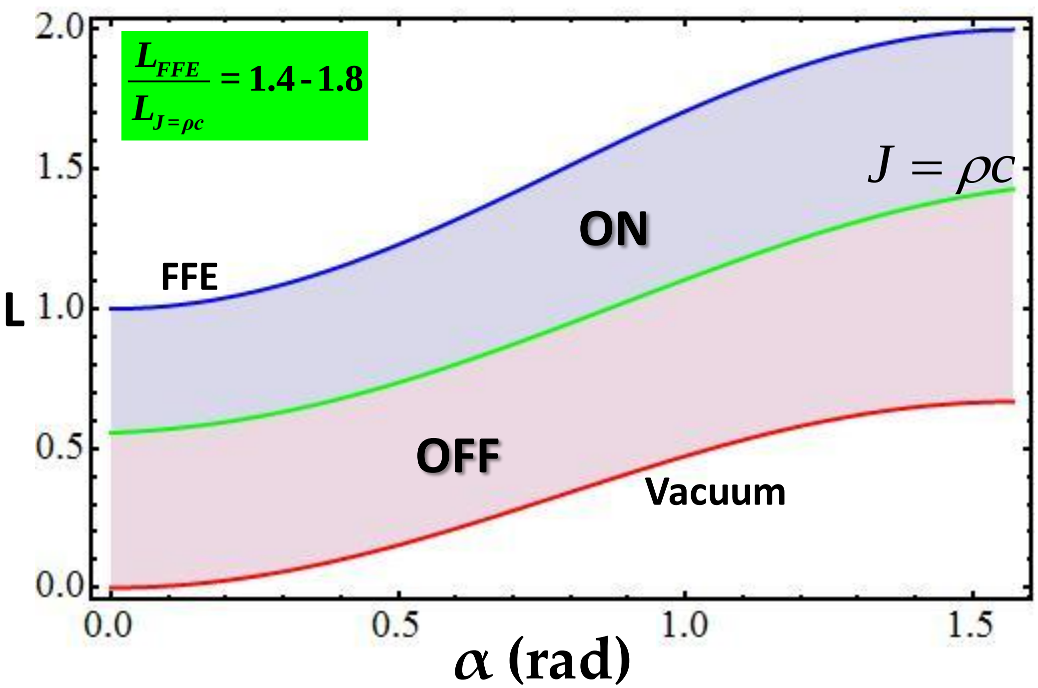
The implications of such an oscillatory behavior which involves an electric field that alternates direction, may in fact provide an account of the pulsar coherent radio emission, as such a behavior is the essential ingredient of cyclotron maser emission (Melrose 1978; Levinson et al. 2005; Melrose 2006; Luo & Melrose 2008).

Intermittent Pulsars

- Intermittent pulsars are pulsars found in "on" and "off" radio states (Lyne 2009).
- They exhibit different spin-down rates in their "on" and "off" states.

We found that the ratio of the spin-down rates between the FFE and the $J/\rho c = 1^-$ *magnetospheres* is within 1.*4–1.8*

There have been observed 3 Intermittent Pulsars **PSR B1931+24, PSR J1832+0029** and **PSR J1841-0500** (Kramer et al. 2006 ,Lorimer et al. 2006; Lyne 2009; Camilo et al. 2012) with spin down rate ratios between the "on" and the "off" states **1.5, 1.7, 2.5**, respectively.



We propose that the "on" state correspond to magnetospheres with J/ϱc > 1 and the "off" one with those of J/ϱc < 1, given the necessity of the presence of pairs (accompanied by the radio emission) in the former and their likely absence (and also of radiation) in the latter.

References

- Beloborodov A. M., 2008, ApJL, 683, L41
- Bogovalov S. V., 1999, A&A, 349, 1017
- Camilo F., Ransom S. M., Chatterjee S., Johnston S., & Demorest P., 2012, ApJ, 746, 63
- Contopoulos I., Kazanas D., & Fendt C., 1999, ApJ, 511, 351
- Deutsch A. J., 1955, Annales d'Astrophysique, 18, 1
- Gruzinov A., 1999, ArXiv Astrophysics e-prints, astro-ph/9902288
- Gruzinov A., 2007, ArXiv e-prints, 2007arXiv0710.1875G
- Gruzinov A., 2008, ArXiv e-prints, 2008arXiv0802.1716G
- Harding A. K., & Muslimov A. G., 2001, ApJ, 556, 987
- Kalapotharakos C. & Contopoulos I., 2009, A&A, 496, 495
- Kalapotharakos C., Kazanas D., Harding A., & Contopoulos I., 2012b, ApJ, 749,2
- Kalapotharakos C., Contopoulos I., & Kazanas D., 2012a, MNRAS, 420, 2793
- Kramer M., Lyne A. G., O'Brien J. T., Jordan C. A., & Lorimer D. R., 2006, Science, 312, 549
- Levinson A., Melrose D., Judge A., & Luo Q., 2005, ApJ, 631, 456
- Li J., Spitkovsky A., & Tchekhovskoy A., 2012, ApJ, 746, 60
- Lorimer D. R., et al., 2006, MNRAS, 372, 777
- Lyne, A. G. 2009, in Astrophysics and Space Science Library, Vol. 357, Astrophysics and Space Science Library, ed. W. Becker (Berlin Heidelberg:Springer), 67
- Luo Q., & Melrose D., 2008, MNRAS, 387, 1291
- Melrose D. B., 1978, ApJ, 225, 557
- Melrose D. B., 2006, Chinese Journal of Astronomy and Astrophysics Spl., 6, 020000
- Spitkovsky A., 2006, ApJL, 648, L51
- Timokhin A.N., & Arons J., 2012, ArXiv e-prints, 2012arXiv1206.5819T