PLASMA-PRODUCING GAPS IN THE GLOBAL STRUCTURE OF PULSAR FORCE-FREE MAGNETOSPHERE

Svetlana Petrova

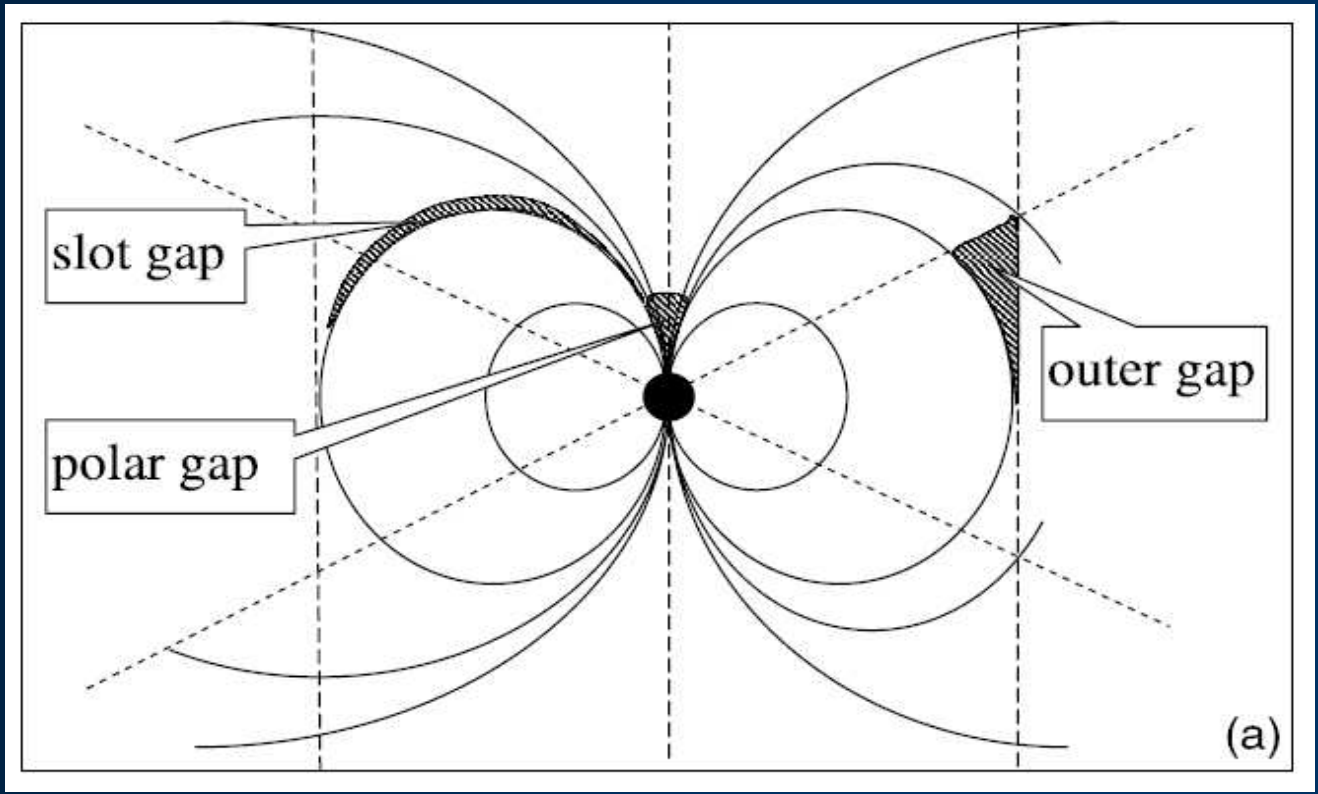
INSTITUTE OF RADIO ASTRONOMY
National Academy of Sciences of Ukraine

Outline

- Summary of existing magnetospheric models
- A new scheme of the pulsar force-free magnetosphere with the gaps and current closure included
- Polar gap adjustment to the force-free magnetosphere allowing for current closure
- Consequences for pulsar emission

Basic models of the magnetosphere

- Vacuum dipole model



Plasma particles affect the electromagnetic field

Self-consistent treatment of fields and particles is necessary

Basic models of the magnetosphere

- Ideal force-free model

$$\boldsymbol{E} \cdot \boldsymbol{B} = 0 \text{ - ideality condition}$$

$$\boldsymbol{j} \times \boldsymbol{B} + \rho_e \boldsymbol{E} = 0 \text{ - force-free condition}$$

- Resistive model

(*Kalapotharakos et al. 2012; Li et al. 2012*)

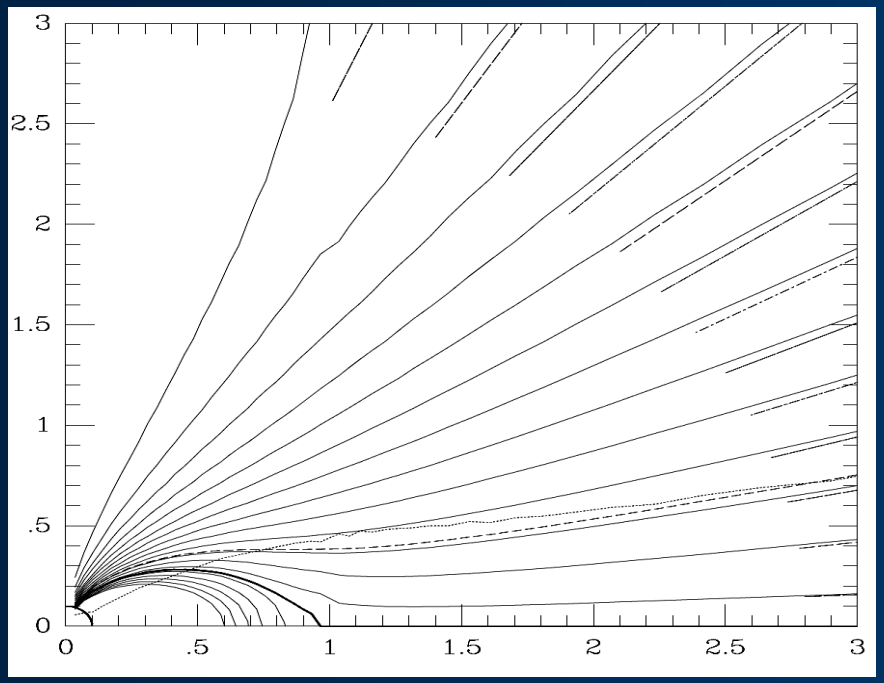
$$\boldsymbol{E} \cdot \boldsymbol{B} \neq 0$$

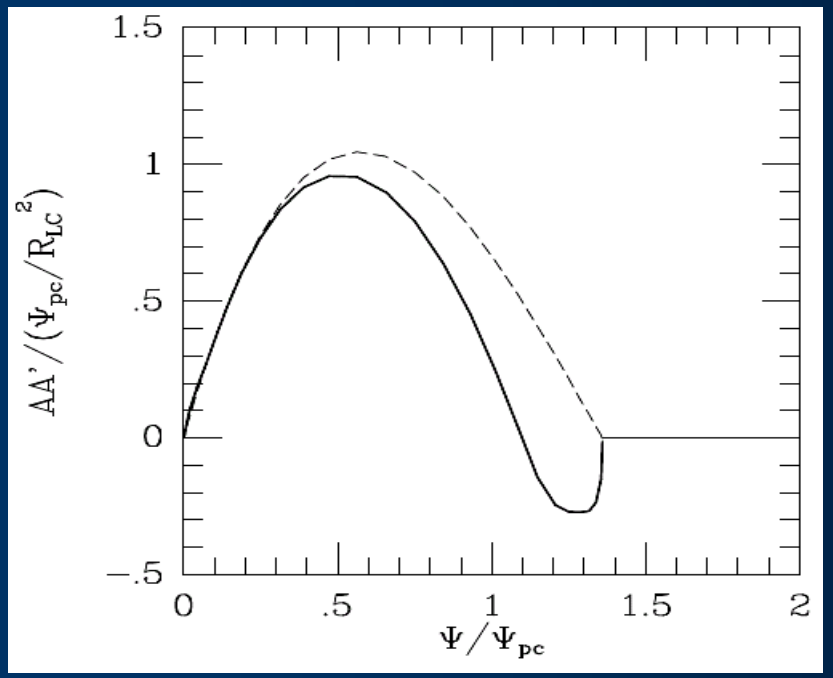
The magnetospheric gaps are still necessary to supply the plasma

It is the gaps that determine the boundary conditions for the force-free zone

Boundary conditions in the force-free problem

- CKF model (*Contopoulos, Kazanas, Fendt 1999*)





The model does not include:

- Magnetospheric gaps
- Current cuircuit closure

- Recent advances (*Parfrey et al. 2012, Petri 2012*)

Continuity of the normal component of $\boldsymbol{B}$ across the stellar surface $(\mathrm{div}\boldsymbol{B} = 0)$

New solution of the pulsar equation

The pulsar equation:

$$(1-\rho^2)\left[\frac{\partial^2 f}{\partial \rho^2}+\frac{1}{\rho}\frac{\partial f}{\partial \rho}+\frac{\partial^2 f}{\partial z^2}\right]-\frac{2}{\rho}\frac{\partial f}{\partial \rho}=-A\frac{dA}{df}$$

The multipolar solution:

$$f/f_0 = 1-\cos\theta+\sum_{k=1}^{\infty}(a/r)^k\left[P_{k-1}(\cos\theta)-\cos\theta P_k(\cos\theta)\right],$$

$$r=\sqrt{\rho^2+z^2},\quad \theta=\operatorname{atan}(\rho/z)$$

The offset monopole:

$$f=f_0\left[1-(z-a)\Big/\sqrt{(z-a)^2+\rho^2}\right],$$

$$A=f(2-f/f_0)$$

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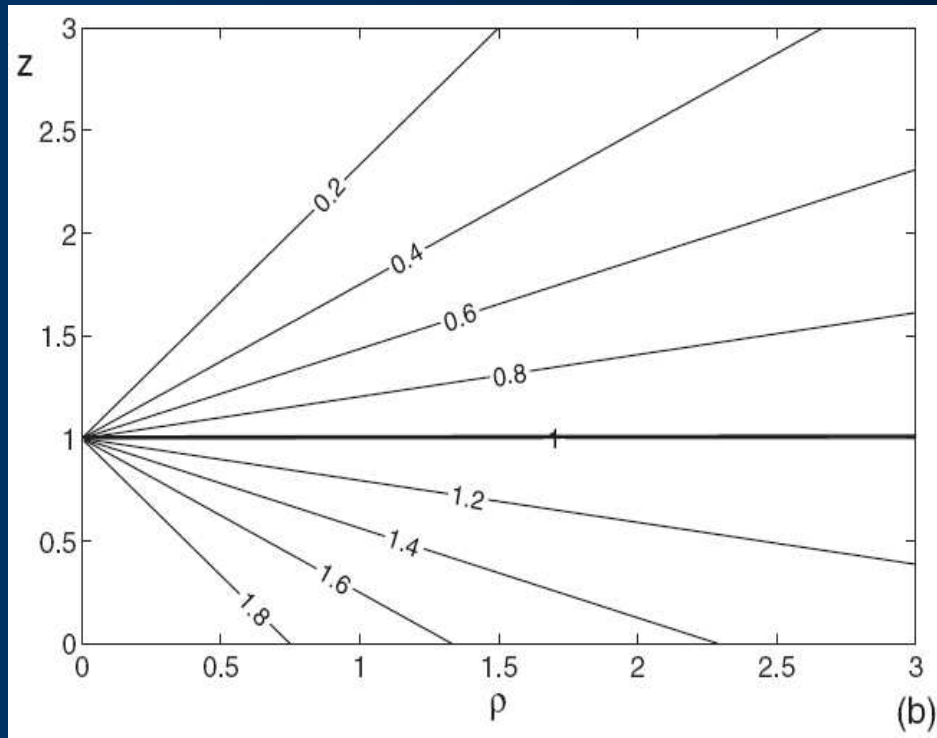
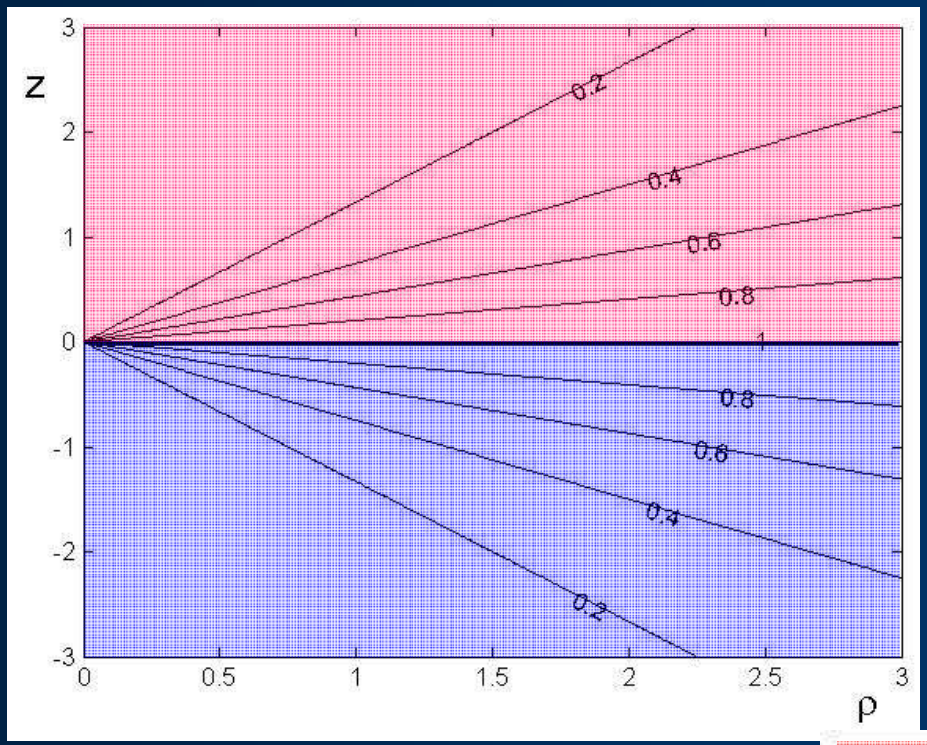
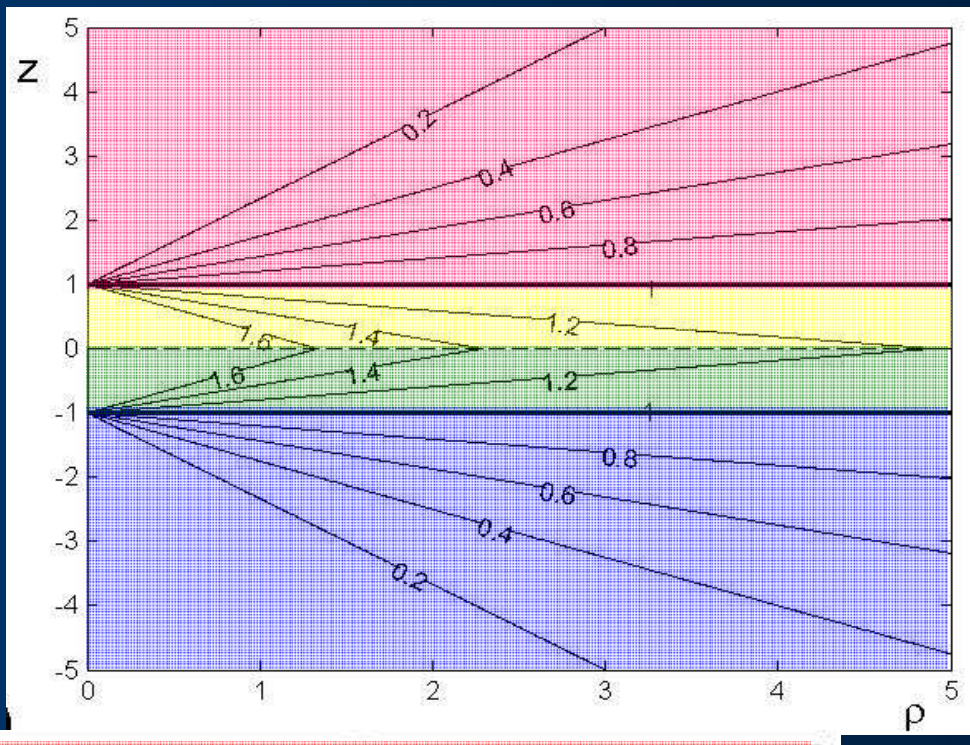


New model of the force-free magnetosphere

Split monopole



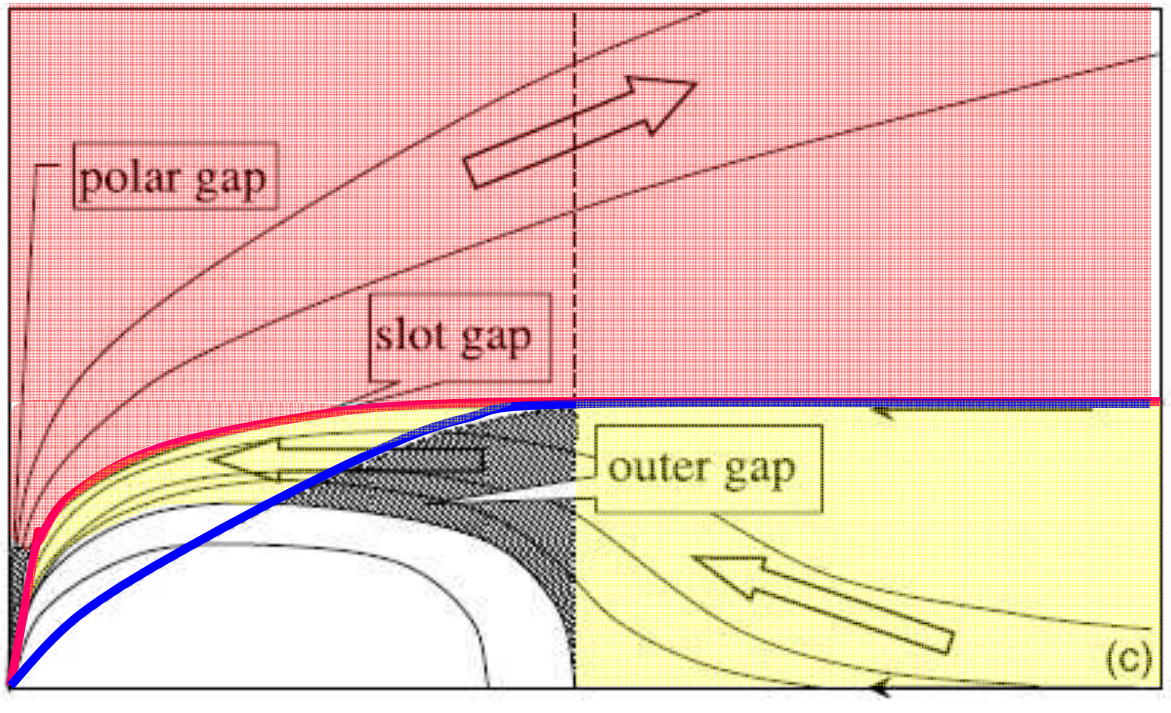
Split-offset monopole



$$A = \Omega f \left(2 - f / f_0\right)$$

The equilibrium condition:

$$\frac{d}{dz}\left(B^2 - E^2\right) = 0 \;\forall\left(A, \Omega\right)$$



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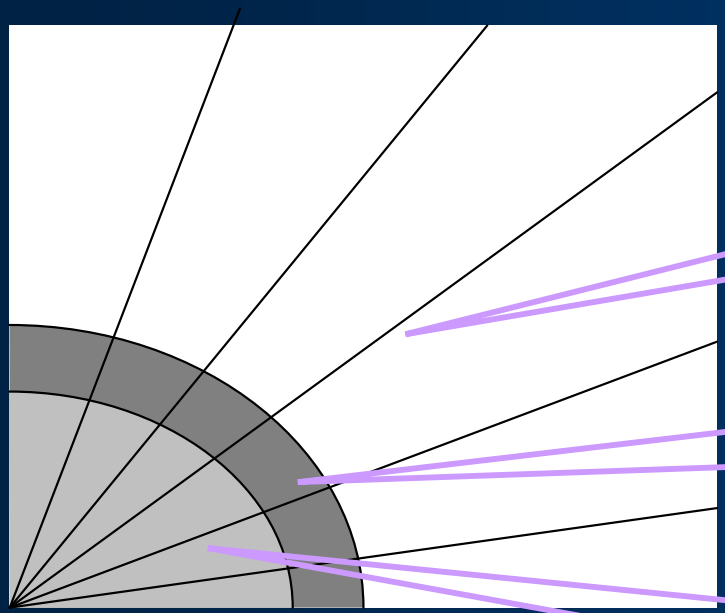
Polar gap and current closure

Space-charge-limited gap → Current closure at the NS

Vacuum gap → Current closure at the PFF



The force-free regime

The transition region

The vacuum regime

Vacuum gap adjustment to the force-free magnetosphere

$$\mathrm{rot}\boldsymbol{E}=0 \;\Rightarrow\; \boldsymbol{E}=-\chi(r-r_0)\left[\frac{\partial f}{\partial\rho},0,\frac{\partial f}{\partial z}\right]+(1-f)\,\delta(r-r_0)\frac{\boldsymbol{r}}{r};$$

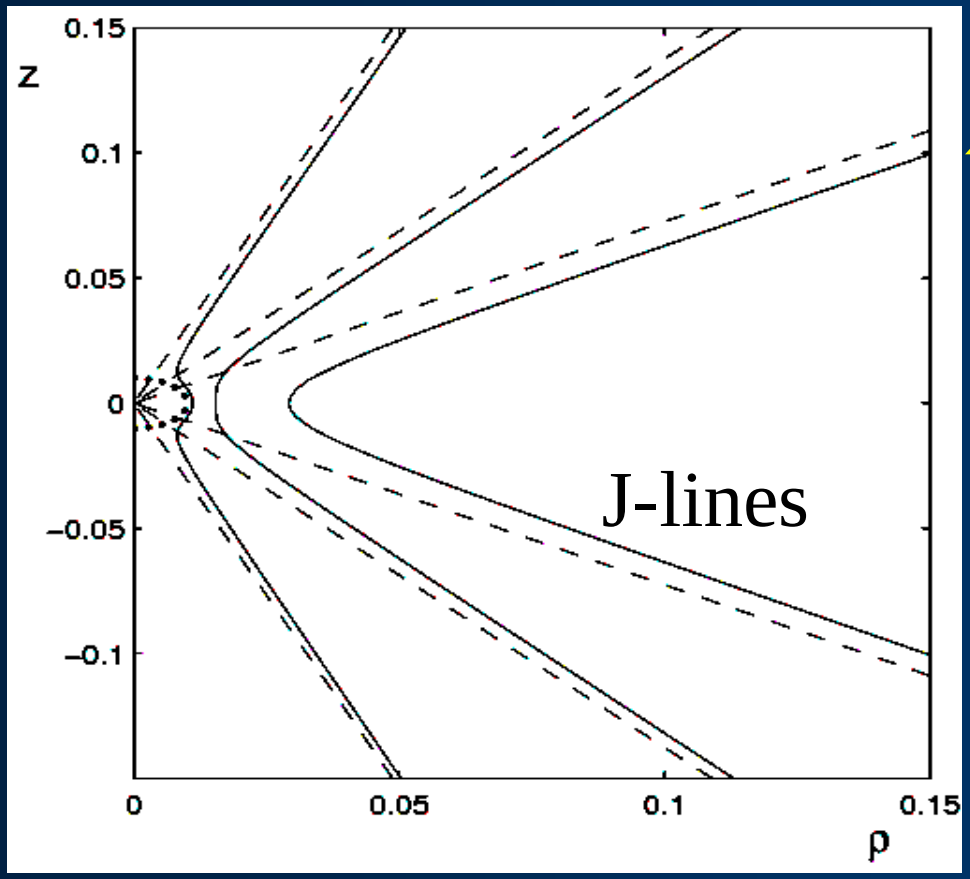
$$\boldsymbol{B}=\frac{1}{\rho}\left(-\frac{\partial f}{\partial z},A\chi(r-r_0),\frac{\partial f}{\partial\rho}\right);$$

$$\rho_e=\mathrm{div}\boldsymbol{E};\quad \boldsymbol{j}=\mathrm{rot}\boldsymbol{B};$$

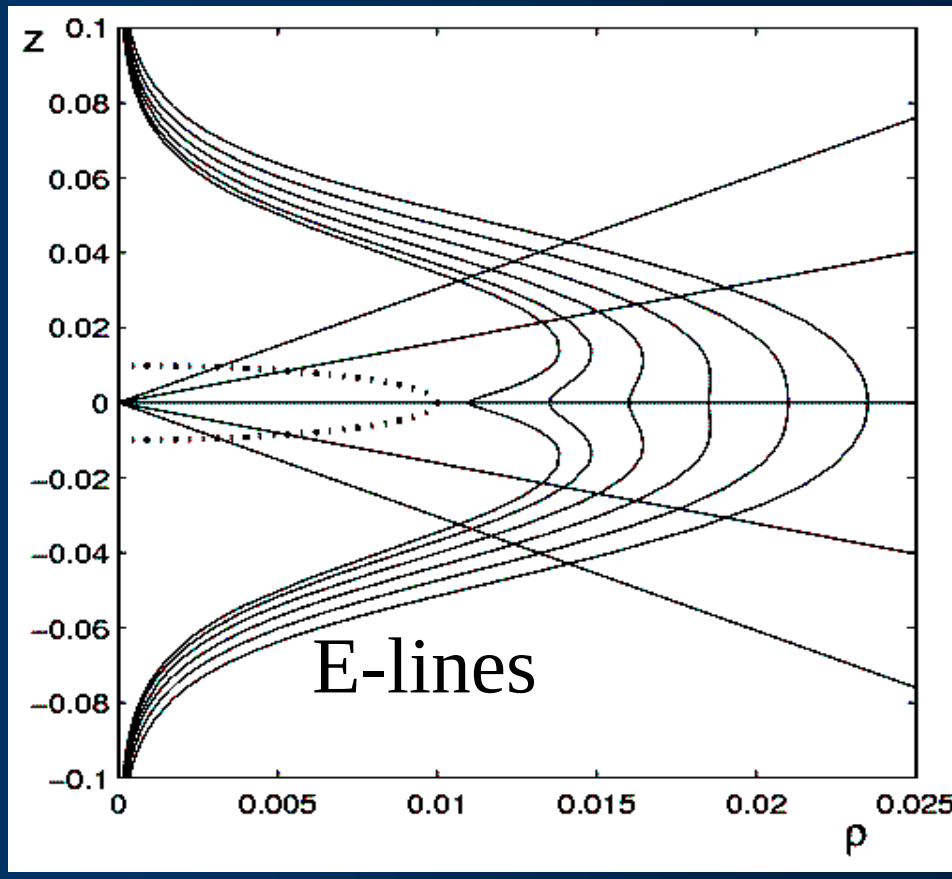
$$\boldsymbol{j}\times\boldsymbol{B}+\rho_e\boldsymbol{E}=\boldsymbol{F}\,\delta(r-r_0);$$

The characteristic scale of the transition region is larger than its altitude above the origin, $h \geq r_0$

Vacuum gap adjustment to the force-free magnetosphere



$$\chi = \frac{r - r_0}{r}$$



$$F_{\parallel} = -\chi(r - r_0)\,\delta(r - r_0)\frac{\rho^2 + 2z^2}{r^4};\quad F_{\perp} = 0;\quad F_{\theta} = \delta(r - r_0)\frac{\rho}{r^4};$$

$$\left(\boldsymbol{r} \times \boldsymbol{F}_{\theta}, \boldsymbol{\Omega}\right)_{tr} = \left(\boldsymbol{E} \times \boldsymbol{B}, \boldsymbol{r}/r\right)_{ff} \Rightarrow$$ The current closure is ideal and results from electromagnetic induction

Consequences for pulsar emission

- The transition region is ~10 times larger than the polar gap height

The radio and vhe emission originates at $r \sim 10 R_*$

- In the case of vacuum gap the current closes at the PFF without dissipation, while in the space-charge-limited case the current closes at the NS and heats the stellar surface

The NS's thermal X-ray emission is different for the two scenarios of the polar gap. The radio emission characteristics should also be distinct. This may explain the difference of the X-ray thermal emission for the two radio emission modes found in Hermsen et al. (2013)

Conclusions

- A new scheme of the pulsar force-free magnetosphere is suggested, which incorporates the polar, outer and slot gaps as well as allows for the current closure
- The pulsar current circuit, completely or partially, closes through the system of magnetospheric gaps. The gaps coexist with the transfield currents
- Adjustment of the vacuum polar gap with the force-free magnetosphere of a monopole is studied in detail. The transition region appears wide. The current closure may be dissipation-free
- The radio and vhe emission originate at $r \sim 10 R_*$
- Radio emission modes may correspond to different scenarios of the polar gap and may be accompanied by distinct thermal X-ray emission