PHYSICS OF RADIO PULSARS 101

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“MAGNETO PLASMIC PROCESSES IN RELATIVISTIC ASTROPHYSICS"

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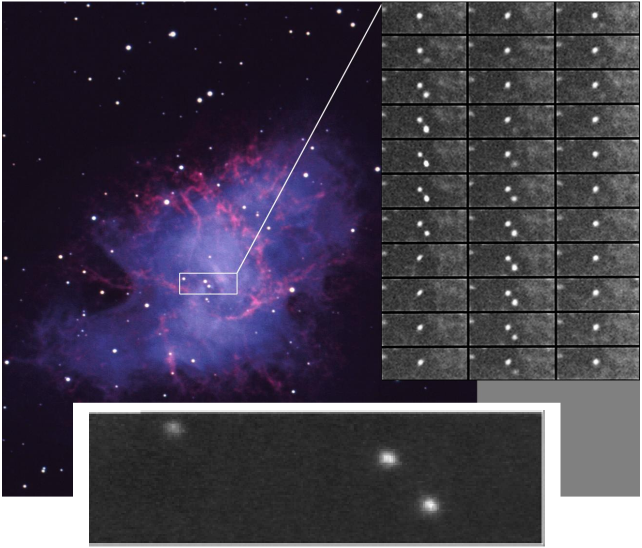
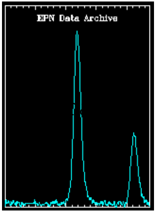
Pulsars: Observational Facts

Pulsating optical source: “Crab pulsar”

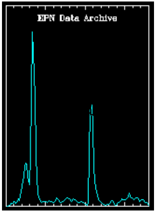


Sounds of Pulsars

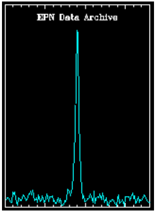
PSR B1937+21
P≈0.0015 s



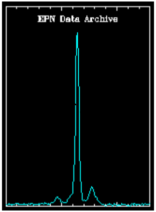
Crab
P≈0.033 s



Vela
P≈0.089 s

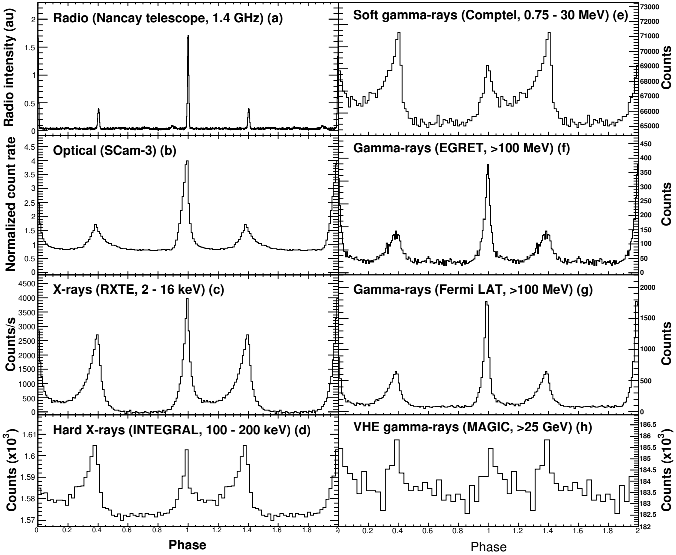


PSR B0329+54
P≈0.71 s

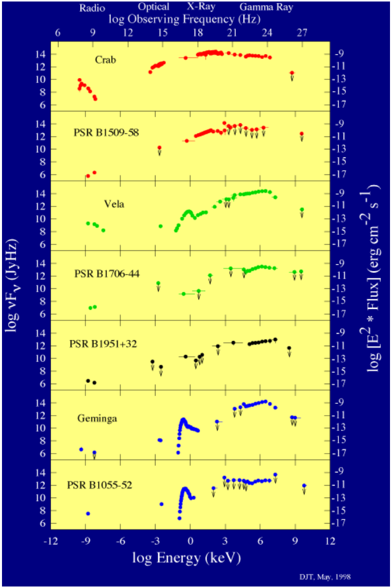


(Credit: Jodrell Bank Centre for Astrophysics)

Crab Pulsar: from Radio to Gamma-rays



Pulsar Multiwavelength Spectra

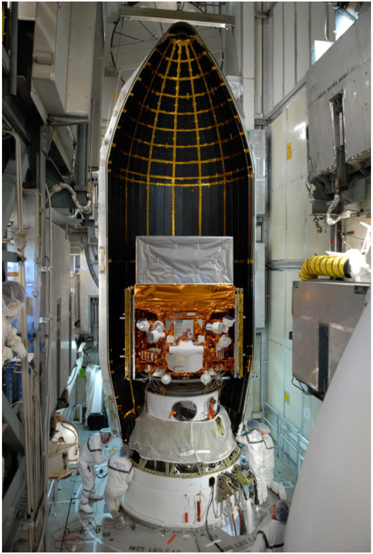


Radio telescopes are huge

Arecibo Observatory – the largest radio telescope

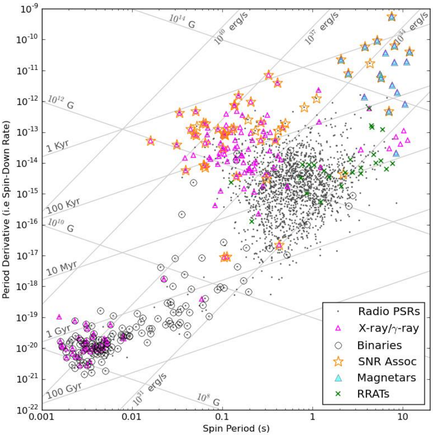
Gamma-ray telescopes are small

Fermi Space Observatory – the largest gamma-ray telescope



$P - \dot{P}$ diagram

Hertzsprung–Russell diagram of pulsar science



Pulsars slow down

$$\frac{d\,E_{rot}}{dt} = \frac{d}{dt}\left(I\Omega^2\right) = -4\pi^2 I\,\frac{\dot{P}}{P^3}$$

due to EM energy losses

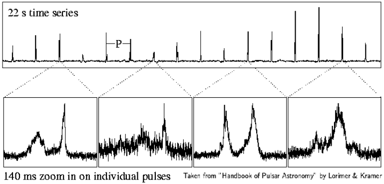
$$W_{EM} = \frac{2\ddot{\mu}^2}{3\,c^2} = \frac{32\pi^4 B^2 R_{NS}^6 \sin^2\alpha}{3\,c^2}\,\frac{1}{P^4}$$

Magnetic field: $B = 3.2 \times 10^{19}\sqrt{P\dot{P}}$ G

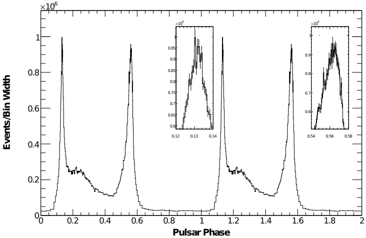
Characteristic age: $\tau = P/(2\dot{P})$

Pulsars: What we see

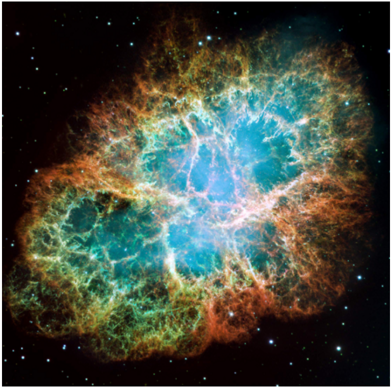
radio:



gamma:



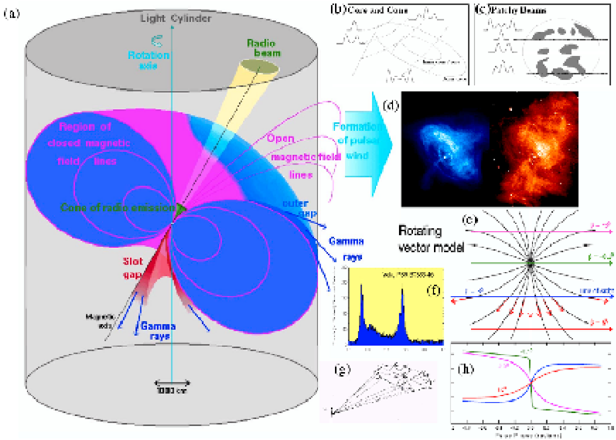
- Pulse peaks are narrow
- Negligible energy budget



- PWNe feed by dense plasma
- Energy goes there

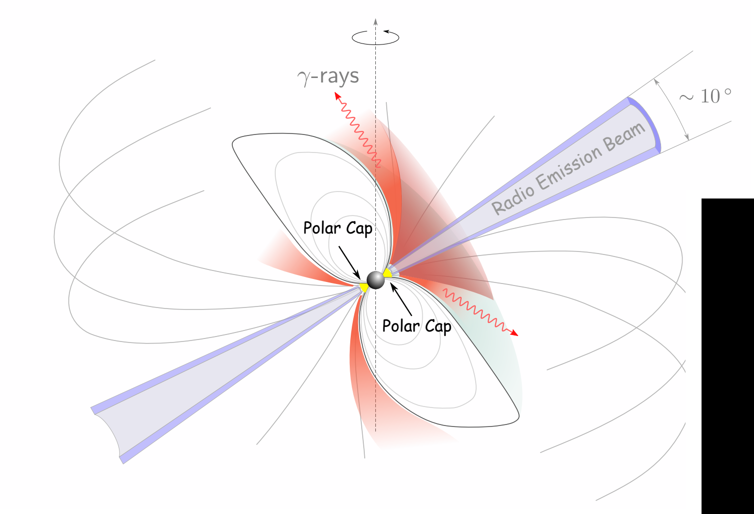
Pulsars: Empirical Model

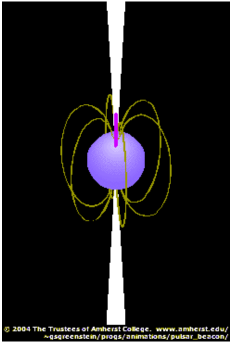
Popular empical pulsar model



Pulsar: rapidly rotating magnetized neutron star

“Electric lighthouse”





Pulsar fact sheet

- Population: > 2000
- Energy source: star's rotation
  stored energy $\sim 10^{51}$ ergs
- Emissivity: up to 10^{38} erg/sec
  $\sim 10^{5}$ of Sun's emissivity
- Periods: ~ 1 msec -10 sec
  Linear velocity of rotation at the surface: up to $\sim 15\% c$!
- Extremely stable clocks:
  stability $\delta P/P$ up to about one part in 10^{15}!

NSs are **the** most extreme objects in the Universe

- Mass: $\sim 1.4 M_{\mathrm{Sun}} \simeq 3 \times 10^{33}$ g
- Radius: 10 km $\simeq 3 r_g$
  only ∼ 3 times larger than a black hole!
- Mean Density: $\sim 10^{15}$ g/cm^3
  Gigantic “atomic nucleus”!
- Magnetic field: $\sim 10^{12}$ G (up to -10^{15} G)
  “Density” of the magnetic field: $\gtrsim 40$ g/cm^3! $[(B^2/8\pi)/c^2]$
- Voltage: $\sim 10^{16}$ V

Density: Osmium 22.59 g/cm^3, Plutonium 19.82 g/cm^3, Iron 7.87 g/cm^3, Water 1 g/cm^3, Air 0.00126 g/cm^3

Pulsar on a tabletop

Basic physical pulsar model

Force-free magnetosphere and electromagnetic cascades

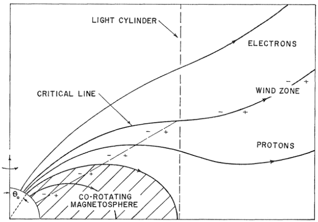


FIG. 1.—Schematic diagram showing the corotating magnetosphere and the wind zone. Star is at lower left.

Goldreich-Julian 1969

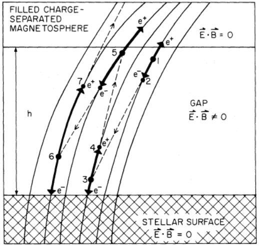
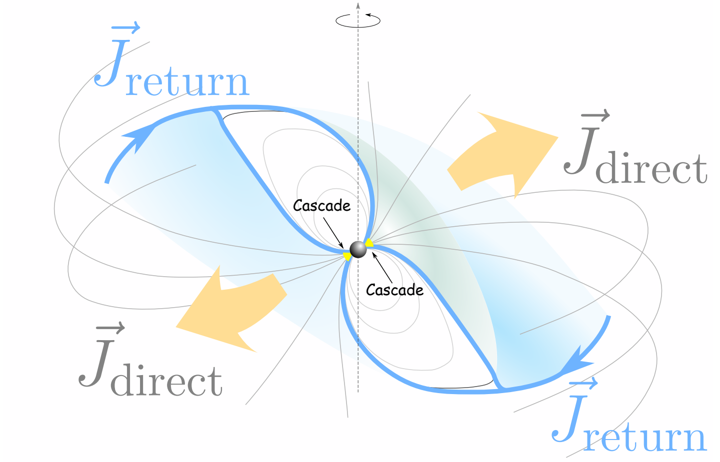


FIG. 3.—Breakdown of the polar gap. The solid lines are polar field lines of average radius of curvature ρ; for a pure dipole field $\rho \sim (Rc/\Omega)^{1/2} \sim 10^8 P^{1/2}$ cm, but for a realistic pulsar one expects $\rho \sim 10^6$ cm if many multipoles contribute near the surface. A photon (of energy $> 2\,mc^2$) produces an electron-positron at *1*. The electric field of the gap accelerates the positron out of the gap and accelerates the electron toward the stellar surface. The electron moves along a curved field line and radiates an energetic photon at *2* which goes on to produce a pair at *3* once it has a sufficient component of its momentum perpendicular to the magnetic field. This cascade of pair production—acceleration of electrons and positrons along curved field lines—curvature radiation—pair production results in a "spark" breakdown of the gap.

Ruderman-Sutherland 1975

Pulsar Magnetosphere: Theorist view

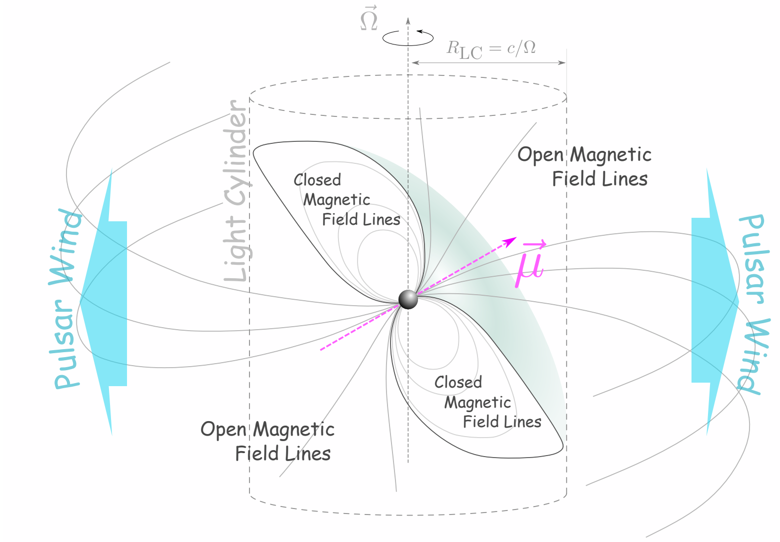
Electrical generator



The magnetosphere is charged
characteristic charge density – "Goldrech-Julian" charge density η_{GJ}.

Pulsar Magnetosphere: Large scale view

“Plasma machine”



MHD-like models

Electrodynamics of pulsar magnetosphere

- The system is relativistic: $\boldsymbol{E} \sim \boldsymbol{B}$
- The system is not charge-neutral: $j \sim \eta c$
  (η is the charge density)
- The system can become charge starved: $n \sim \eta / e$

Force-Free Electrodynamics of pulsar magnetosphere

- MagnetoHydroDynamics:
  Maxwell Equations + Matter Equations

- **Force-Free MHD**:
  Maxwell Equations + $\eta \cdot \boldsymbol{E} + \frac{1}{c}\boldsymbol{j} \times \boldsymbol{B} = 0$

Stationary Configuration: *E* and *B* through Ψ , *I* , Ω_F

In cylindrical coordinates (ϖ, Z, ϕ)

- Magnetic field:

$$\boldsymbol{B} = \frac{\boldsymbol{\nabla}\Psi \times \boldsymbol{e}_\phi}{\varpi} + \frac{4\pi}{c}\frac{I}{\varpi}\boldsymbol{e}_\phi$$

- Electric field:

$$\boldsymbol{E} \equiv -\frac{\Omega_F}{c}\nabla\Psi$$

- magnetic flux trough the sufrace S – $\Phi_{\rm mag}$

$$\Phi_{\rm mag} \equiv \int_S \boldsymbol{B}\, d\sigma = \; 2\pi\Psi$$

- *Outflowing* poloidal current – J:

$$J \equiv \int_S \boldsymbol{j}\, d\sigma = \; 2\pi I$$

Stationary Configuration: Pulsar equation

The force-free equation of motion:

$$\eta \boldsymbol{E} + \frac{1}{c}[\boldsymbol{j} \times \boldsymbol{B}] = 0 \quad \Rightarrow \quad (\nabla \cdot \boldsymbol{E})\boldsymbol{E} + [[\nabla \times \boldsymbol{B}] \times \boldsymbol{B}] = 0\,.$$

The poloidal component of it is the pulsar equation

$$\left(1 - \frac{\Omega_{\mathrm{F}}{}^2 \varpi^2}{c^2}\right) \Delta\Psi - \frac{2}{\varpi}\partial_\varpi \Psi + \left(\frac{4\pi}{c}\right)^2 I \frac{dI}{d\Psi} - \frac{\varpi^2}{c^2}\Omega_{\mathrm{F}} \frac{d\Omega_{\mathrm{F}}}{d\Psi} (\nabla\Psi)^2 = 0$$

(Grade-Shafranov equation for poloidal magnetic field)

There are two integrals of motion in the Grad-Shafranov equation – I and Ω_{F} . If they are known one can solve the equation for Ψ .

Dimensionless pulsar equation

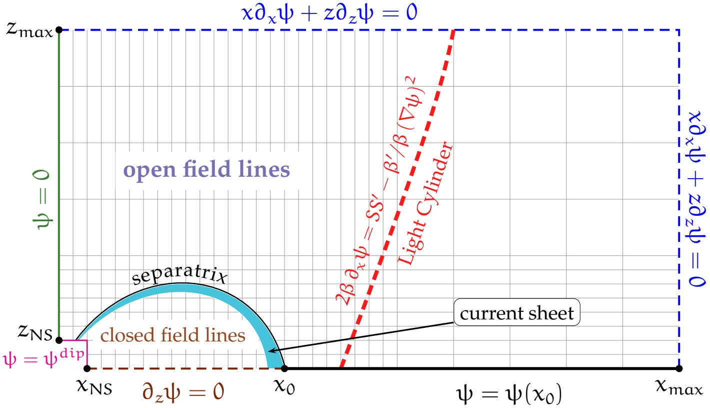
$$
\begin{aligned}
(\beta^2 x^2 - 1)(\partial_{xx}\psi + \partial_{zz}\psi) + \frac{\beta^2 x^2 + 1}{x}\partial_x\psi - \\
-S\frac{dS}{d\psi} + x^2\beta\frac{d\beta}{d\psi}(\nabla\psi)^2 &= 0\,. \qquad (1)
\end{aligned}
$$

At the light cylinder the coefficient by second derivatives goes to zero and the pulsar equation has the form

$$
2\beta\,\partial_x\psi = S\frac{dS}{d\psi} - \frac{1}{\beta}\frac{d\beta}{d\psi}(\nabla\psi)^2\,. \qquad (2)
$$

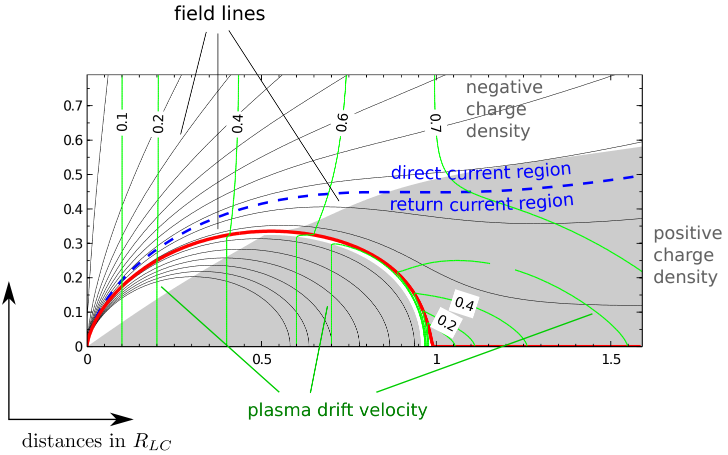
$\Omega_{\rm F}(x,z) \equiv \beta(x,z)\,\Omega$, distances in Light Cylinder radii

Calculation domain



Pulsar Magnetosphere in 2D

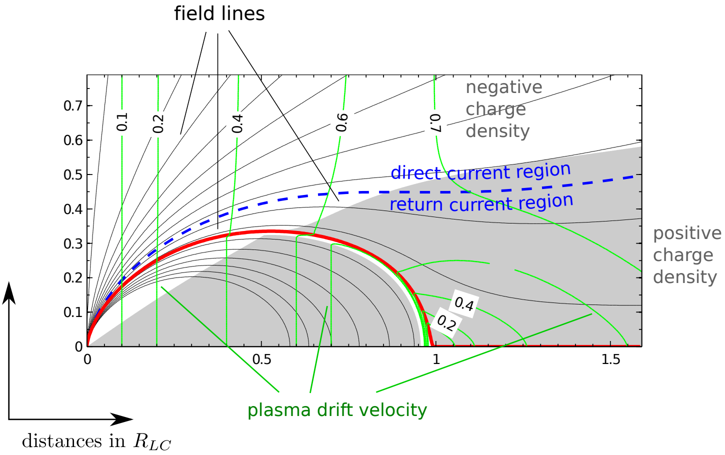
Numerical simulations of Force-Free magnetosphere



(Timokhin 2006)

Pulsar Magnetosphere in 2D

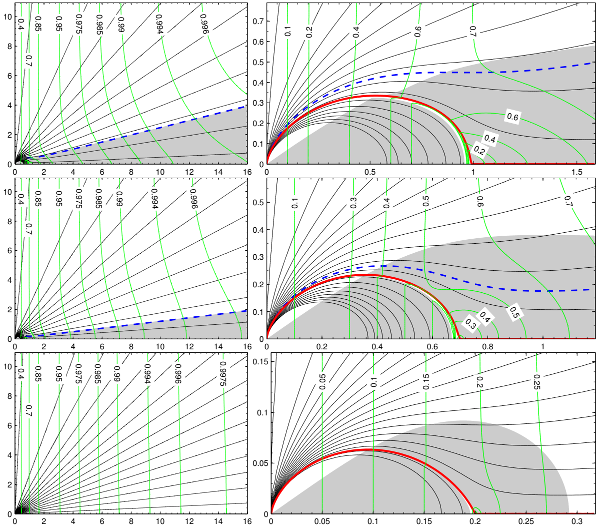
Numerical simulations of Force-Free magnetosphere



(Timokhin 2006)

Pulsar Magnetosphere in 2D: different configurations

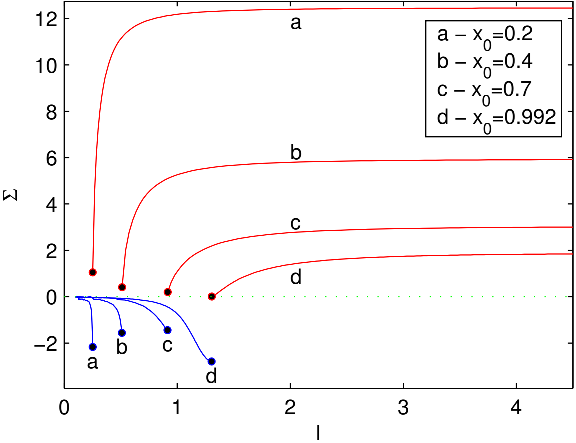
Solutions with the different sizes of the corotation zone



(Timokhin 2006)

Surface charge density of the current sheet

Σ is normalized to $0.5\mu/R_{\rm LC}^2$



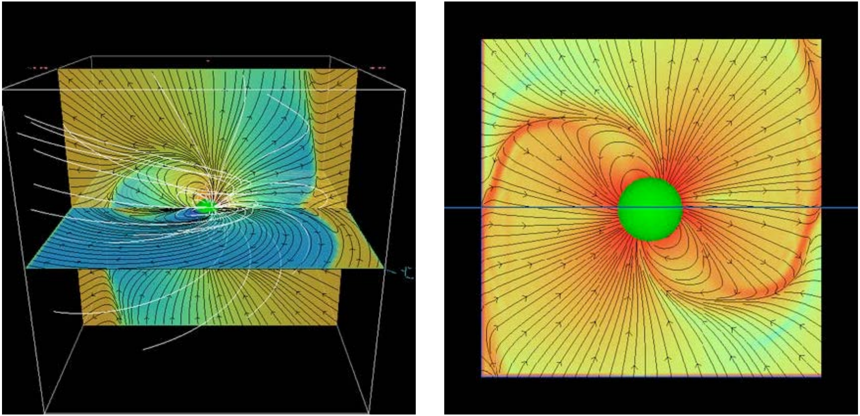
(Timokhin 2006)

Force-Free Electrodynamics

$$
\begin{aligned}
\frac{1}{c}\frac{\partial \mathbf{E}}{\partial t} &= \nabla \times \mathbf{B} - \frac{4\pi}{c}\mathbf{j} \\
\frac{1}{c}\frac{\partial \mathbf{B}}{\partial t} &= -\nabla \times \mathbf{E} \\
\mathbf{j} &= \frac{c}{4\pi}\nabla \cdot \mathbf{E}\frac{\mathbf{E} \times \mathbf{B}}{B^2} + \frac{c}{4\pi}\frac{(\mathbf{B} \cdot \nabla \times \mathbf{B} - \mathbf{E} \cdot \nabla \times \mathbf{E})\mathbf{B}}{B^2}
\end{aligned}
$$

Pulsar Magnetosphere in 3D: Structure of inner parts

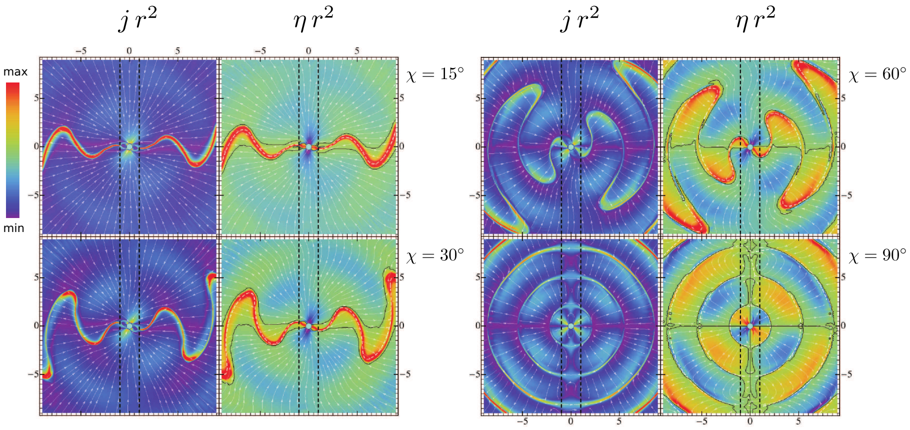
Numerical simulations of Force-Free magnetosphere



(Spitkovsky 2006)

Pulsar Magnetosphere in 3D: Outer parts - Wind Zone

Numerical simulations of Force-Free magnetosphere

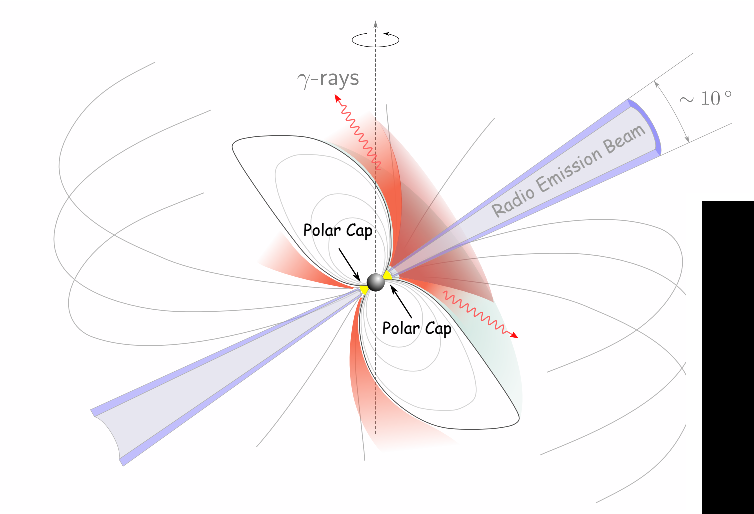


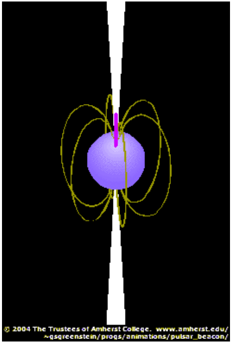
(Kalapotharakos et al. 2012)

Plasma Creation

Pulsar: a plasma gun

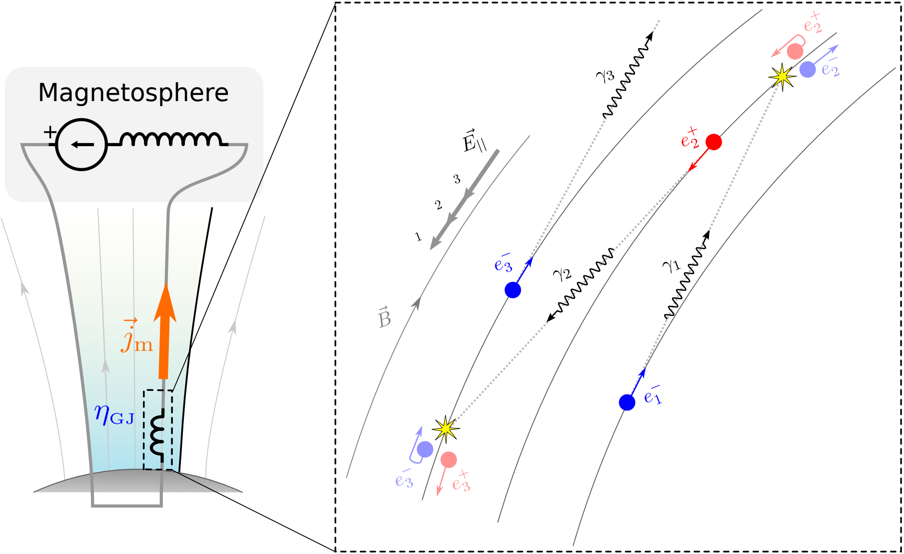
Emission is a whistle of a locomotive



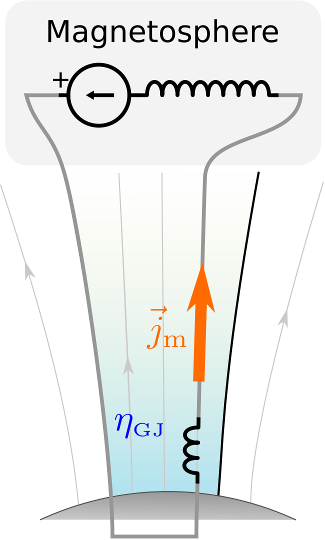


Plasma creation in the polar cap

Cascades are electromagnetically driven



Polar Cap Electrodynamics



- Rotation of the NS

$$\nabla \cdot \boldsymbol{E} = 4\pi(\eta - \eta_{\rm GJ})$$

- Twist of magnetic field lines

$$\nabla \times \boldsymbol{B} = \frac{4\pi}{c} j + \frac{1}{c}\frac{\partial \boldsymbol{E}}{\partial t}$$

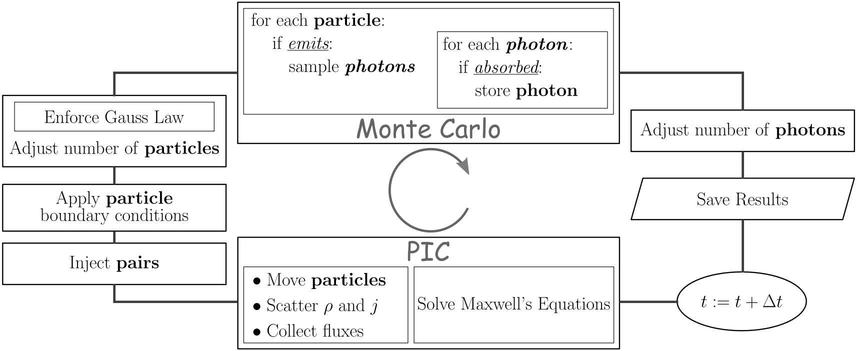
- $\boldsymbol{E} = 0$ if both

$$\eta = \eta_{\rm GJ}$$

$$j = j_{\rm m} \equiv \frac{c \nabla \times \boldsymbol{B}}{4\pi}$$

Numerical code for cascace modeling *PAMINA*

*P*IC *A*nd *M*onte-Carlo code for cascades *IN A*strophysics



[AT 2010, AT & Arons 2013]

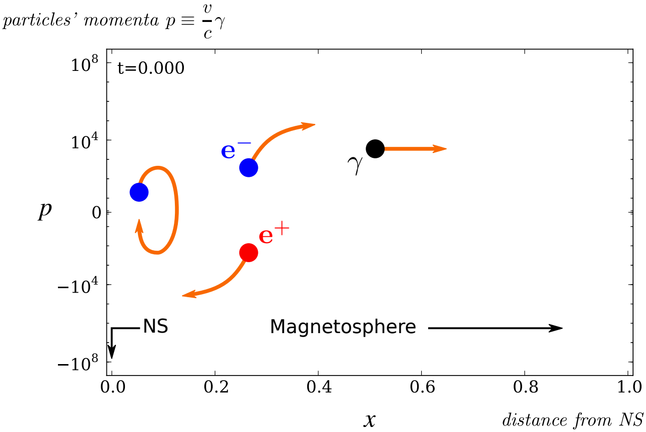
Modeling from the first principles:

Particle acceleration $\leftrightarrow$ Electric field **Particle-In-Cell**

Particles $\rightarrow$ Photons $\rightarrow$ Particles(Pairs) **Monte Carlo**

Limit cycle: series of discharges

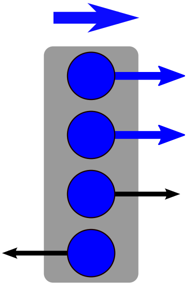
No particles extraction from the NS

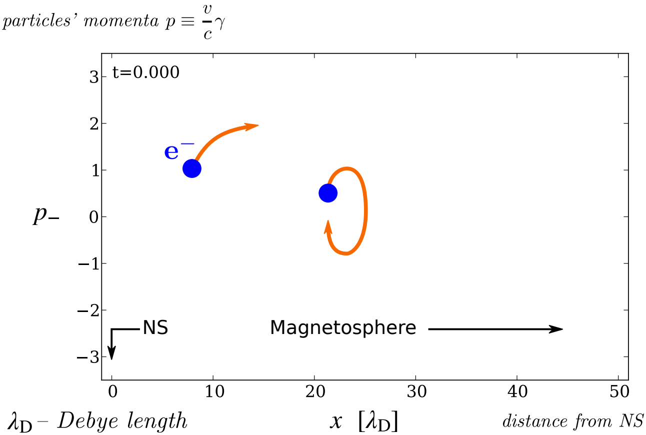


• electrons • positrons • γ-rays

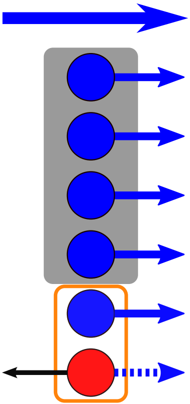
Formation of a low energetic flow for $j/j_{\mathrm{GJ}} < 1$

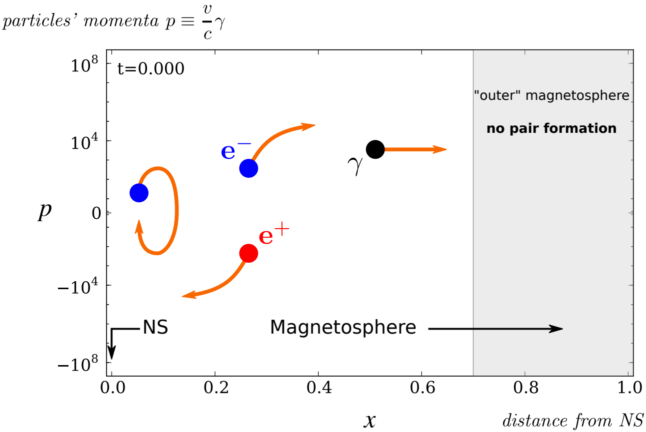
Free particle extraction from the NS





SCLF: Discharges in super-GJ flow $\quad j/j_{\mathrm{GJ}} > 1$

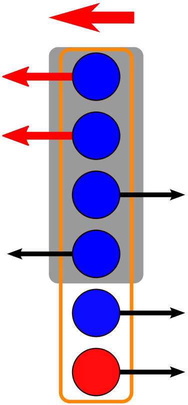


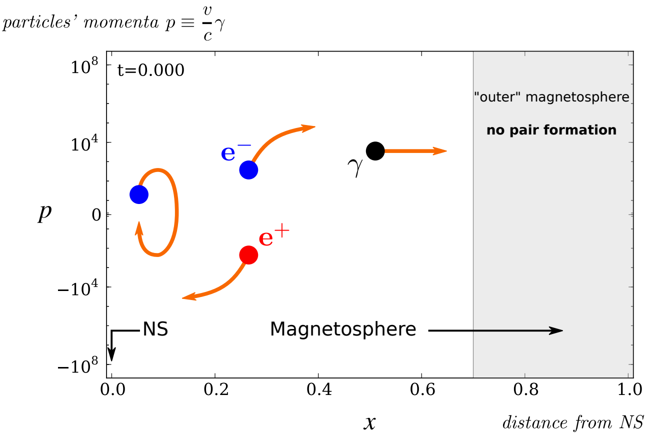


• electrons • positrons • γ-rays • protons

Discharges in the return current $j/j_{\mathrm{GJ}} < 0$

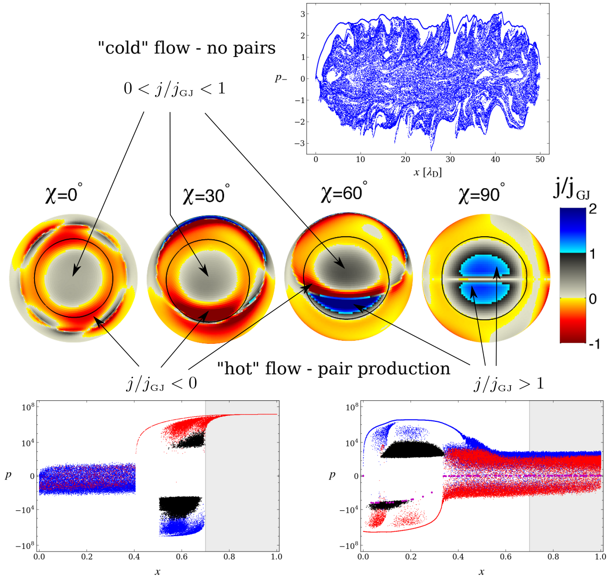
The same for both RS and SCLF





• electrons • positrons • γ-rays

Free particle extraction from the NS (Timokhin & Arons'13)



Particles' momenta:
p~[0,10]

electrons

Polar cap currents

Particles' momenta:
p~[0,10^7]

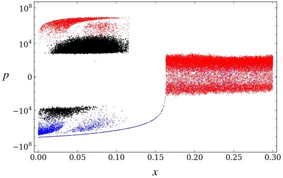
electrons
positrons
photons

No particle extraction from the NS

(Timokhin '10)

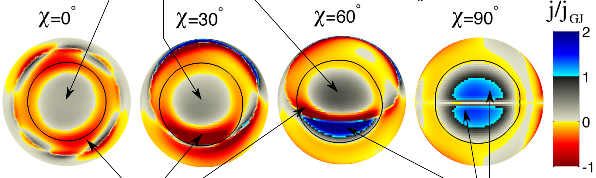
"hot" flow everywhere,
pair production:

near NS $0 < j/j_{GJ} < 1$



Particles' momenta:
p~[0,10^7]

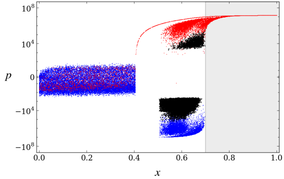
electrons
positrons
photons

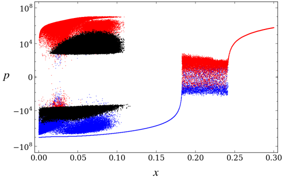


Polar cap currents

far from NS $j/j_{GJ} < 0$

near NS $j/j_{GJ} > 1$



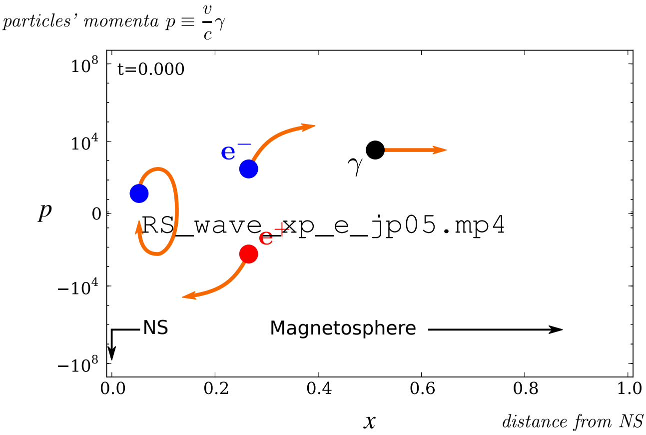


Particles' momenta:
p~[0,10^7]

electrons
positrons
photons

Waves during discharge

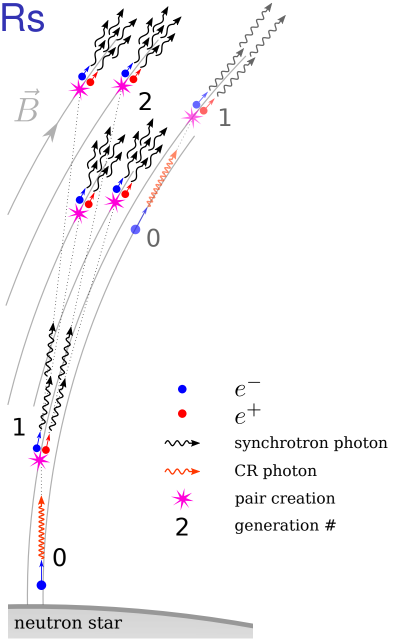
It did not escape our attention. . .



Full cascade in young PSRs

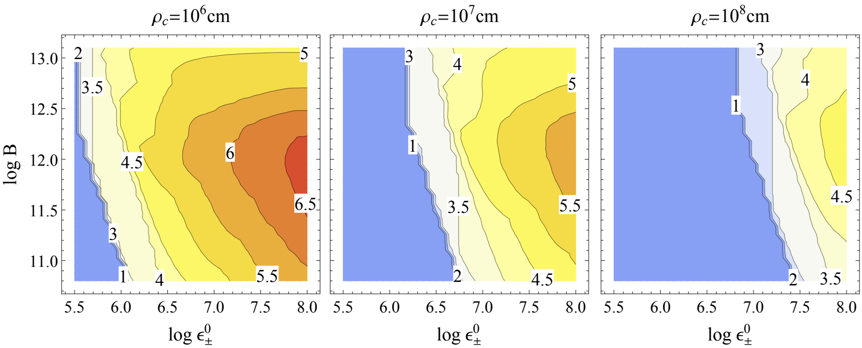
Synchrotron cascade

Curvature Radiation



Multiplicity of cascade initiated by a single particle

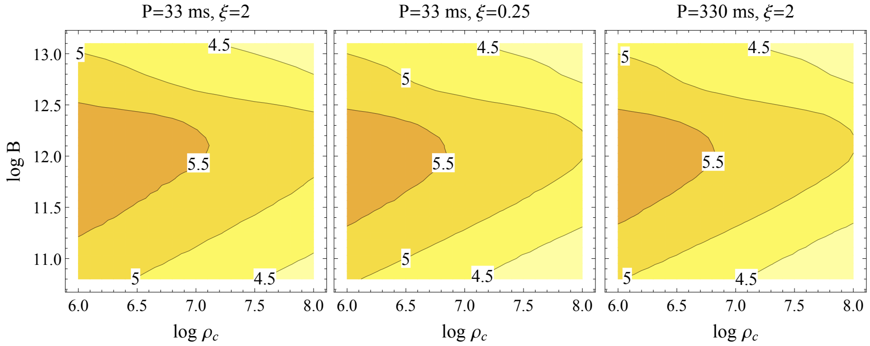
Multiplicity of polar cap cascade initiated by a particle with the energy ϵ_0



(Timokhin & Harding '15)

Multiplicity of polar cap cascade: $\kappa \sim 10^5$

Multiplicity of polar cap cascade with particle acceleration taken into account



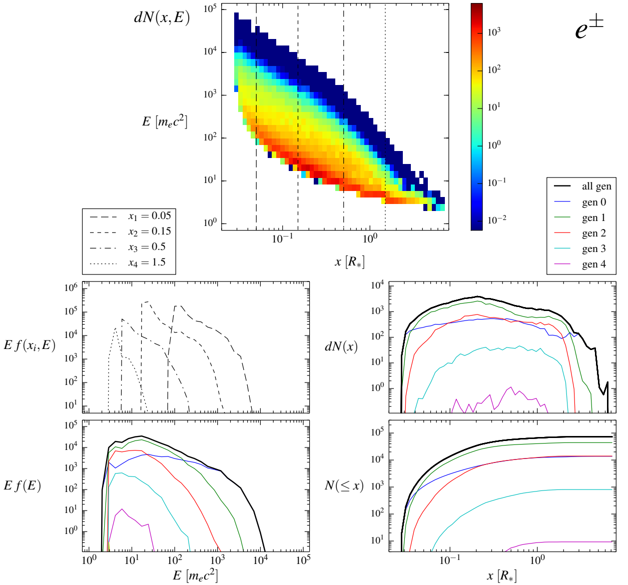
(Timokhin & Harding '15)

Dependence on ρ_c partially cancels out:

- small $\rho_c \longrightarrow$ high splitting efficiency, but low primary particle energy
- large $\rho_c \longrightarrow$ low splitting efficiency, but high primary particle energy

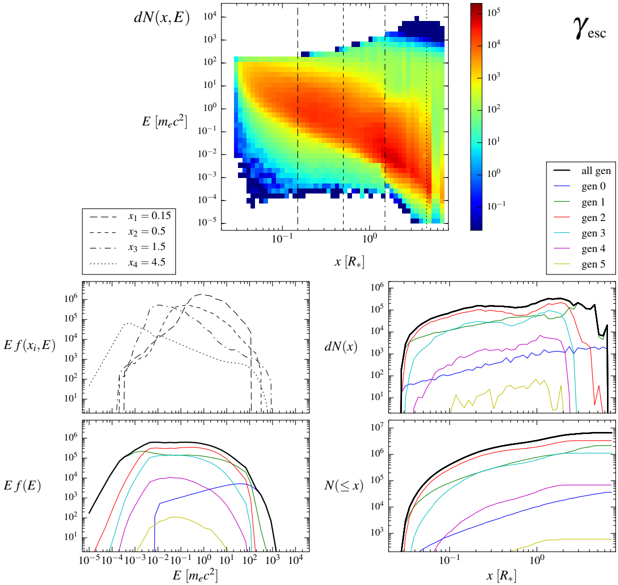
Cascade Portrait:pairs

(Timokhin & Harding ’15)



Cascade Portrait: photons

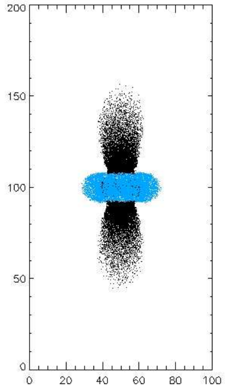
(Timokhin & Harding '15)



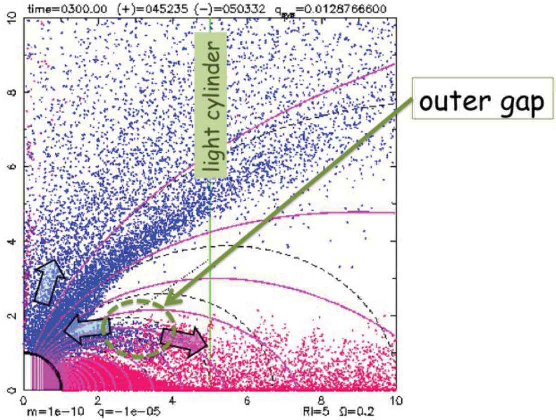
Global Kinetic Models

Magnetosphere Formation

Still an open question

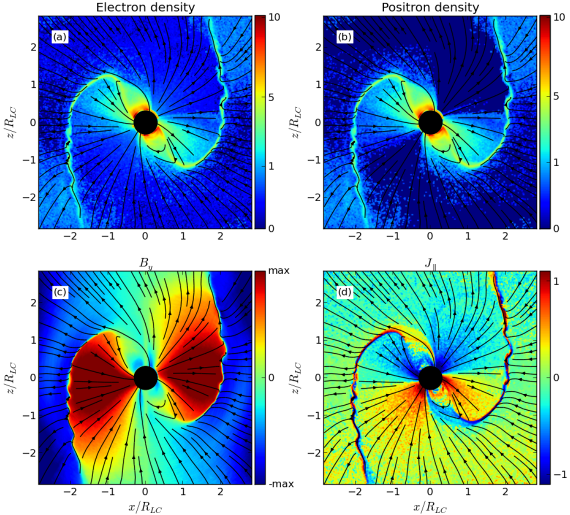


(Spitkovsky 2003)



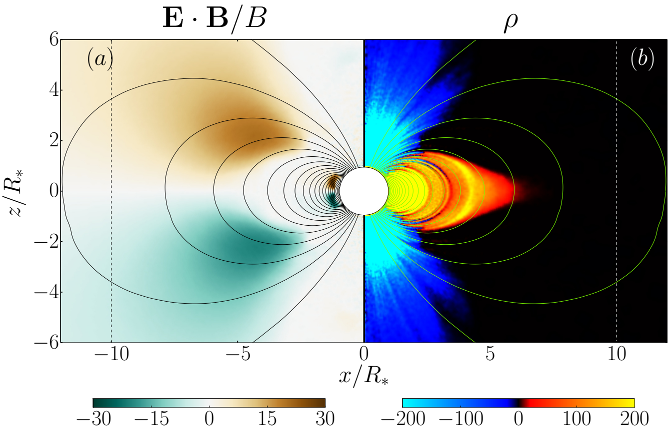
(Shibata 2013)

3D Global Kinetic Model of the Magnetosphere



(Philippov, Spitkovsky, Cerutti ’14)

2D Global Kinetic Model of the Magnetosphere



(Chen & Beloborodov '14)

Biggest problems

Pulsar slowdown

Breaking index – never 3!

Breaking index:

$$n_b \equiv \frac{\ddot{\Omega}\Omega}{\dot{\Omega}^2}$$

for magnetodipolar as wells as all force-free models $n_b = 3$!

PSR	Frequency (Hz)	n	Ref.
B1509−58	6.633598804	2.839±0.001	[11]
J1119−6127	2.4512027814	2.684±0.002	[12]
J1846−0258	3.062118502	2.65±0.1	[11]
		2.16±0.13	[13]
B0531+21 (Crab)	30.22543701	2.51±0.01	[14]
B0540−69	19.8344965	2.140±0.009	[11, 15]
J1833−1034	16.15935711	1.8569±0.001	[16]
B0833−45 (Vela)	11.2	1.4±0.2	[17]
J1734−3333	0.855182765	0.9±0.2	[18]

Table 1: Selected pulsars adopted from [19, 18, 6].

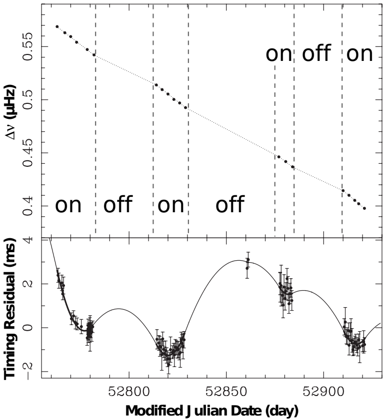
never the case!

Spindown rate variations: PSR B1931+24

Two different states with different slowdown rates

PSR B1931+24

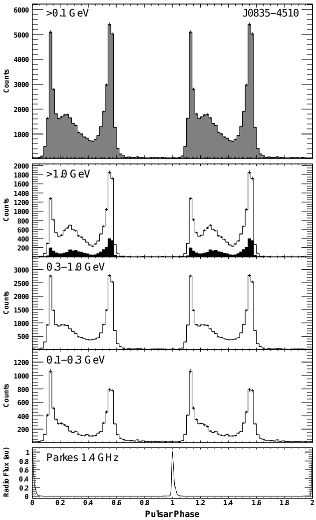
$P = 0.813\,\mathrm{s},\ W_{on}/W_{off} = 1.5$



(Kramer et al. 2006)

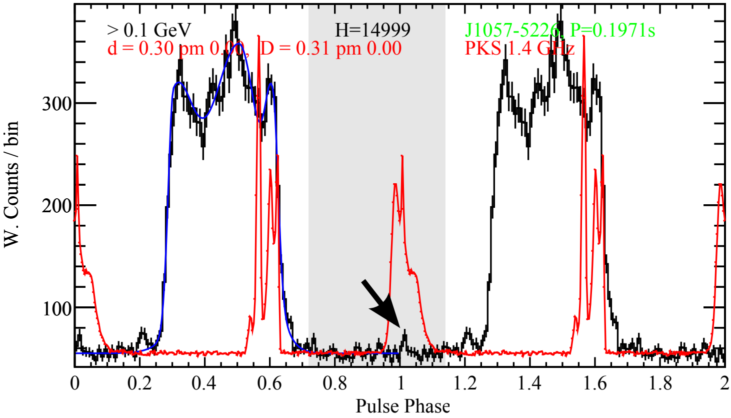
No high energy emission from polar caps

Fermi sees gamma-rays from the outer magnetosphere only



PSR J1057-5226: Polar cap emission?

May be γ-ray emission from polar caps is in a lower energey range?



Conclusions

- This is a very difficult problem
- We still have no quantitative pulsar model