Kinetic modelling of pulsar magnetospheres

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Pulsars shine throughout the electromagnetic spectrum

A large fraction of the pulsar spindown is released in light, in particular in the gamma-ray band. => Efficient particle acceleration!

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Most Galactic accelerators are pulsars

~ 100 gamma-ray pulsars

Pulsars emitting gamma rays young and ms, i.e., rotation-powered

[2nd Fermi-LAT pulsar catalog]
Pulsars are efficient particle accelerators

L_γ \sim 1-10\% Spin-down

How does the star spin-down?
How is this energy transferred to particles and radiation?

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Typical gamma-ray pulsar signal

How and where are particle accelerated and radiate?

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Two peaks lightcurves

Hard power-law + exponential cut-off

[2\textsuperscript{nd} Fermi-LAT pulsar catalog]
Rotation of the field lines induce electric field:

$$E = \frac{R \Omega B}{c}$$

Potential difference pole/equator:

$$\Delta \Phi = \frac{R^2 \Omega B}{c} \approx 10^{16} \text{ V}$$

(for a Crab-like pulsar)
Elements of a pulsar magnetosphere: plasma filled

Dipole in vacuum is not a good model!

Copious pair creation in the polar caps

\[ \Delta \Phi_{pc} = \frac{R^3 \Omega^2 B}{C^2} \approx 10^{14} V \]

Potential polar cap (Crab):

\( E.B \neq 0 \)

\( \gamma \)-B absorption

Curvature

\[ \text{Dipole in vacuum is not a good model!} \]

\[ \text{Copious pair creation in the polar caps} \]

\[ \text{Synchrotron} \]

\[ \text{\( \gamma \)-B absorption} \]

\[ \text{Curvature} \]

\[ \text{Potential polar cap (Crab):} \]

\[ \Delta \Phi_{pc} = \frac{R^3 \Omega^2 B}{C^2} \approx 10^{14} V \]

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Elements of a pulsar magnetosphere: plasma filled

- "Open" field lines
  - Outflowing plasma and Poynting flux

- "Closed" field lines
  - Plasma confined, co-rotating "Dead zone"

Magnetosphere

- Light-cylinder radius: $R_{LC} \Omega = c$
  - Here corotation is impossible!

Wind region

- Toroidal field, $B_\varphi$
  - Jump in $B$ => Current Sheet

Rotation axis

- Similar to the heliospheric current sheet.

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Proposed sites for particle acceleration

Acceleration in gaps, \( E.B \neq 0 \)
\( \gamma \)-ray: curvature radiation
- Radio emission?
- \( \gamma \)-rays?
Unlikely because absorbed by B

"Polar-cap" type model

Favored by \( \gamma \)-ray observations

"Outer/slot-gap" type model

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Proposed sites for particle acceleration

Particle acceleration via relativistic reconnection

\( \gamma \)-ray: Synchrotron


Models dependent on the geometry of the magnetosphere

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Insight from the MHD approach
(Force Free / Resistive Force Free / Full MHD)

There is no analytical solution for the magnetosphere, need for numerical simulations!

Numerical solution of the aligned rotator
[Contopoulos et al. 1999]

Numerical solution of the inclined rotator
[Spitkovsky 2006]

Caveat: The fluid approach does not capture the microphysics (particle acceleration nor radiation)
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Insight from the MHD approach  
(Force Free / Resistive Force Free / Full MHD)

Ideal Force-Free field geometry with prescribed emitting field lines  
Bai & Spitkovsky 2010a,b

Non-ideal Force-Free with prescribed resistivity  

Favor high-energy emission from the outer magnetosphere + current sheet  
Ad-hoc accelerating/radiating zones, large uncertainties  
Need for self-consistent approach

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PIC simulations!
The Particle-In-Cell (PIC) approach

Follow motion of millions of charged particles and evolved the electromagnetic fields

Particles evolve in continuous space

(E,B) fields known on the grid

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The numerical setup: an aligned rotator (2D)

Reflecting wall

Dipole in vacuum

Injection of particles

Absorbing layer
(no plasma, λE, λ*B terms)

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Philipppov & Spitkovsky 2014
Chen & Beoborodov 2014
Cerutti et al. 2015
Belyaev 2015

Light cylinder radius

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Toroidal magnetic field

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Cerutti et al. 2015
Global PIC simulations with discharge

Ref: Chen & Beloborodov 2014; Philippov et al., 2015

The stellar rotation impose a twist on the field lines, hence a current outside the light-cylinder. This current must be matched at the polar cap.

Electrons alone carry enough current
=> No discharge needed, no acceleration!


=> Low-multiplicity plasma (κ~1) are in contradictions with observations where κ>>1
General relativistic effects may be a way out!

Ref: Beskin 1990; Muslimov & Tsygan 1992; Sakai & Shibata 2003

Lense-Thirring frequency:

\[ \omega_{LT} = \frac{2}{5} \Omega_* \frac{r_s}{R_*} \left( \frac{R_*}{r} \right)^3 \]

Frame-dragging effect reduces the stellar rotation

\[ \frac{J_{\hat{r}}}{\rho_{G,JC}} \approx \left( \frac{J_{\hat{r}}}{\rho_{G,JC}} \right)_{flat} \frac{1}{1 - \omega_{LT}/\Omega_*}. \]

Significant only at the star surface, no changes at the light-cylinder!

=> Less particles are extracted from the polar cap

=> But the same current is needed

\{ Need a discharge \}

=> Particle acceleration!
2D GR PIC simulations

Development of GRPIC code [Philippov et al. 2015b] : Zeltron 3+1 GR electrodynamics

Courtesy of Sasha Philippov
2D GR PIC simulations

Time-dependent discharge of the polar-cap: **Origin of the radio emission?**

Power in stripes $W \sim 10^{-2} L_0$, enough to the observed radio emission

*Courtesy of Sasha Philippov*
**3D PIC with radiation reaction force**

**Zeltron code**: [http://benoit.cerutti.free.fr/Zeltron/](http://benoit.cerutti.free.fr/Zeltron/)

**Assumption**: Large plasma supply provided by the star surface = **Efficient pair creation**

- **Radiation reaction force**
  \[
  \frac{d(\gamma m_e v)}{dt} = q \left( E + \beta \times B \right) + g,
  \]

- **Emitted radiation spectra**:
  \[
  F_\nu (\nu) = \frac{\sqrt{3} e^3 \tilde{B}_\perp}{m_e c^2} \left( \frac{\nu}{\nu_c} \right) \int_{\nu/\nu_c}^{+\infty} K_{5/3}(x) dx,
  \]
  \[
  \tilde{B}_\perp = \sqrt{(E + \beta \times B)^2 - (\beta \cdot E)^2},
  \]

- Apply for **synchrotron and curvature** radiation

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- **(log(r)×\theta×\phi)**: 1024×256×256
Particle / radiation mean energy ($\chi=30^\circ$)

Cerutti, Philippov & Spitkovsky 2016

Particle acceleration via relativistic reconnection in the current sheet
High-energy radiation is synchrotron radiation

Particle energy in the sheet given by:

\[
\sigma_{\text{LC}} = \frac{B_{\text{LC}}^2}{4\pi \Gamma n_{\text{LC}} m_e c^2} \approx 50
\]

(here)

See also in 2D axisymmetric Cerutti et al. 2015
Particle / radiation spectra

Particle acceleration and emission of energetic radiation decreases with pulsar inclination

\[ \nu_0 \equiv \frac{3eB_\star}{4\pi m_e c} \]

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Cerutti, Philippov & Spitkovsky 2016
High-energy radiation flux ($\nu > \nu_0, \chi = 0^\circ$)

Presence of spatial irregularities due to kinetic instabilities in the sheet (e.g., kink and tearing modes, see also Philippov et al. 2015a)
High-energy radiation flux ($\nu > \nu_0$, $\chi = 30°$)

$i=30$ - Phase=0.00 - Positrons -
High-energy radiation flux ($\nu > \nu_0$, $\chi = 60^\circ$)

Small contribution from the wind regions: Could be due to reconnection induced inflow towards the sheet (Tchekhovskoy et al. 2013)
High-energy radiation flux ($\nu > \nu_0$, $\chi = 90^\circ$)

Even for the orthogonal rotator, high-energy photons are concentrated within the equatorial regions where most of the spin-down is dissipated.
**Observed** high-energy radiation flux \((\nu > \nu_0, \chi = 0^\circ)\)

**Gray** : Total flux (all directions)

**Color** : Observed flux

\[i = 0 - \text{Phase}=0.00 - \text{Positrons} -\]

Spatial extension of the observed emission in the sheet

\(\Rightarrow\) Formation of a **caustic**

HE flux concentrated close to the light-cylinder

Observer
**Observed** high-energy radiation flux ($\nu > \nu_0$, $\chi = 30^\circ$)

Gray: Total flux (all directions)

Color: Observed flux

Light curve shaped by the geometry of the current sheet

\[ i = 30 - \text{Phase} = 0.00 - \text{Positrons} - \]
Two-peaked lightcurves are very generic
One peak per crossing of the current sheet

Blue: Positronic emission
Red: Electronic emission

\[ \alpha = 90^\circ \] \hspace{2cm} \[ \alpha = 60^\circ \] \hspace{2cm} \[ \alpha = 45^\circ \]

Fermi-LAT second pulsar catalog

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Cerutti, Philippov & Spitkovsky 2016
Particle acceleration and origin of the $e^+ / e^-$ asymmetry

2D

Tracked positrons

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Particle acceleration and origin of the $e^+ / e^-$ asymmetry
Particle acceleration and origin of the $e^+/e^-$ asymmetry

2D (aligned pulsar)
Particle acceleration and origin of the $e^+/e^-$ asymmetry

In the co-rotating frame

Tracked positrons

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Cerutti, Philippov & Spitkovsky 2016
Particle acceleration and origin of the $e^+/e^-$ asymmetry

In the co-rotating frame

Tracked electrons
Application to the Crab pulsar

**Fermi-LAT**

![Graph showing counts vs. angle with peaks at 60° and 130°, labeled with ΔΦ≈0.4 and x3 magnification.]  

**PIC model**

χ=60°, α=130°  

Consistent with the nebula morphology in X-rays  

[e.g. Weisskopf+2012]

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(Incoherent) Polarization signature: Observations

[Graph showing polarization signature with symbols for Optical, 2PA, Polarized flux, IP, and MP.]
(Incoherent) Polarization signature : PIC

PIC model
\[ \chi = 60^\circ, \alpha = 130^\circ \]

Degree of polarization : \[ \Pi \approx 15-30\% \]
The Crab pulsar as we may see it!

Gray: Total flux (all directions)
Color: Observed flux

i=60 - Phase=0.00

Pulse profile
Conclusions

- **Global PIC simulations is the way to go** to solve particle acceleration in pulsars.

- **General relativity** helps at producing pairs in the polar cap, and hence at emitting *radio waves*.

- Simulations demonstrate the major role of *relativistic reconnection* in particle acceleration.

- High-energy emission could be *synchrotron radiation from the current sheet* \( \gtrsim R_{LC} \).

- **Pulse profile and polarization** provide robust constraints on Crab pulsar inclination and viewing angles.

- More work needed to **compare simulations to observations**.