Pulsar magnetospheres and pulsar winds

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6 unpublished papers


11 published papers (radio pulsars)


Several gaps

There are several gaps in radio pulsars:
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• inner gap
Several gaps

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• inner gap,
• outer gap
Several gaps

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• inner gap,
• outer gap,
• slot gap
Several gaps

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- inner gap,
- outer gap,
- slot gap,
- and the gap between observers and theoreticians.
Several gaps

There are several gaps in radio pulsars:
- inner gap,
- outer gap,
- slot gap,
- and the gap between observers and theoreticians.

The last problem is the most serious one.
A Problem

- Theoreticians (in general) do not formulate predictions which can be checked.
- Observers (in general) do not produce test measurements.

The reason – there is NO pure experiment.
Let us return to the very ground…

- What we know definitely?
- Are we sure?

I.S. Shklovsky (1916-1985)

V.L. Ginzburg (1916-2009)

Ya.B. Zeldovich (1914-1987)
Radio pulsars – rotating solitary* neutron stars

- Mass \( M \sim 1.4 \, M_\odot \)
- Radius \( R \sim (10–15) \, \text{km} \)
- Rotation period \( P \sim 1 \, \text{s} \)
- Magnetic field \( B_0 \sim 10^{12} \, \text{G} \)
- Radio luminosity \( L_r \sim 10^{28} \, \text{erg/s} \) (~\(10^{-4} – 10^{-6}\))
- Coherent mechanism: \( T \sim 10^{28} \, \text{K} \) (~\(10^{40} ????\))
Everything is clear?

- Mechanism of the coherent radio emission.
- NS works as PSR for both orientation of $\Omega$ and $m$, or for only one (which?)
- Neutron star radius $R$?
- $B \sim 10^{12}$ G? 
  Up to $B \sim 10^{15}$ G for magnetars?
- Electron-positron plasma?
- Current or magneto-dipole?
- Inner gap – how it works?
- Outer gap – does it exist?
Everything is clear?

• Mechanism of the coherent radio emission.
• We see NS as PSR for both (besides $m$ and $m$, or for only one which?)
• Neutron star radius $R$?
• $B \sim 10^{12} \, \text{G}$?
  Up to $B \sim 10^{15} \, \text{G}$ for magnetars?
• Electron-positron plasma?
• Current or magneto-dipole?
• Inner gap – how it works?
• Outer gap – does it exist?
Pulsar chronology

- Ancient world (… – 1967)
- Hellas (1967 – 1973)
- Rome (1973 – 1983)
- Dark ages (1983 – 1999)
- Industrial revolution (2006 – 2012)
- Modern time (2012 – …)
Hellas (1967 – 1973)

- Key electrodynamical idea
- Goldreich-Julian charge density
- Michel magnetization parameter (maximum bulk Lorentz-factor)
- Sturrock (multiplicity parameter)
  \[ \gamma + B \rightarrow e^+ + e^- + B \]
- Radhakrishnan-Cooke RVM ('hollow cone' model)

\[ \rho_{GJ} = -\frac{\Omega \cdot B}{2\pi c} \]

\[ \sigma = \frac{\Omega^2 \Psi_{\text{tot}}}{8\pi^2 c^2 \mu \eta} \]

\[ \lambda = \frac{n^{(\text{lab})}}{n_{GJ}} \]
Hellas (1967 – 1973)

- Key electrodynamical idea
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\[ \rho_{GJ} = -\frac{\Omega \cdot B}{2\pi c} \]
\[ j_{GJ} = \rho_{GJ} c \]
\[ \sigma = \frac{\Omega^2 \Psi_{tot}}{8\pi^2 c^2 \mu \eta} \]
\[ \lambda = \frac{n^{(lab)}}{n_{GJ}} \]
The key electrodynamic idea
(N.S.Kardashev, 1964; F.Pacini, 1967)

Magneto-dipole (vacuum) radiation

\[ W_{\text{tot}} = -J_r \Omega \dot{\Omega} \approx \frac{1}{6} \frac{B_0^2 \Omega^4 R^6}{c^3} \sin^2 \chi \]

\[ W_{\text{tot}} \sim 10^{32} \text{ erg/s} \]

In reality is it not so (magnetosphere is filled with plasma), but is enough for evaluation
The key electrodynamic idea

The moment of the truth – Crab pulsar

\[ P = 0.033 \text{ s}, \]
\[ \frac{dP}{dt} = 4 \times 10^{-13} \]

Full energy loss

\[ W_{\text{tot}} = -I_r \Omega \frac{d\Omega}{dt} \sim 5 \times 10^{38} \text{ erg/s} \]

The life time

\[ \tau = \frac{P}{(dP/dt)} \sim 1000 \text{ years} \]

Detection of optical pulsations
The key electrodynamic idea

The moment of the truth – Crab pulsar

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Detection of optical pulsations
Corotation, light cylinder, polar cap

\[ R_L = \frac{c}{\Omega} \]
“Hollow cone” model

\[ p.a. = \arctan \left( \frac{\sin \chi \sin \varphi}{\sin \xi \sin \chi - \sin \xi \cos \chi \cos \varphi} \right) \]
Hellas (1967 – 1973)

Main results
• Stability of pulsation – neutron star rotation
• Energy source – kinetic energy of rotation
• Mechanism of energy loss – electrodynamics
• Pair creation is the key process
• RVM ("hollow-cone" model)

Open question
How does it work.
Rome (1973 – 1983)

- Mestel equation
- Pulsar equation + first analytical solutions
- Ruderman-Sutherland gap (no injection from the surface)
- Arons gap (free escape)
- BGI – full screening of the magneto-dipole radiation
- BGI – possibility of a domain with $E > B$
Force-free approximation

One can neglect energy of particles

\[ \frac{1}{c} \mathbf{j} \times \mathbf{B} + \rho_e \mathbf{E} = 0, \]

Pulsar equation

\[- \left( 1 - \frac{\Omega_F^2 \varpi^2}{c^2} \right) \nabla^2 \Psi + \frac{2}{\varpi} \frac{\partial \Psi}{\partial \varpi} - \frac{16\pi^2}{c^2} I \frac{dI}{d\Psi} + \frac{\varpi^2}{c^2} (\nabla \Psi)^2 \Omega_F \frac{d\Omega_F}{d\Psi} = 0\]

First solutions

\[- \left(1 - \frac{\Omega_F^2 \omega^2}{c^2}\right) \nabla^2 \Psi + \frac{2}{\omega} \frac{\partial \Psi}{\partial \omega} - \frac{16 \pi^2}{c^2} I \frac{dI}{d\Psi} + \frac{\omega^2}{c^2} \left(\nabla \Psi\right)^2 \Omega_F \frac{d\Omega_F}{d\Psi} = 0\]
Incline rotator, $I = 0$

Orthogonal Rotator, \( I = 0 \)


No energy flux through the light cylinder

\[
B_\varphi \propto (1 - x_r^2)^2
\]
Current losses

For current loss mechanism is necessary to have

- Plasma in the magnetosphere,
- regular poloidal magnetic field,
- rotation (inductive electric field $E$, EMF $\delta U$),
- longitudinal current $I$ (toroidal magnetic field $B$).

$$W_{\text{tot}} = I \delta U$$
Current losses

\[ W_{\text{tot}} = -\Omega \cdot K \]

\[ K = \frac{1}{c} \int \left[ r \times [J_s \times B] \right] \, dS \]

\[ \nabla \times J_s = j_n \]

\[ J_s = \frac{I}{2\pi R \sin \theta} e^\theta \]
Current losses

\[ W_{\text{tot}} = c \frac{B_0^2 \Omega^4 R^6}{c^3} i_0 \]

\[ i_0 = j_\parallel / j_{GJ} \]

\[ W_{\text{tot}}^{(BGI)} \approx i_s^A \frac{B_0^2 \Omega^4 R^6}{c^2} \cos^2 \chi \]

for GJ current (BGI)
Orthogonal rotator


\[ j_{GJ} \approx \frac{\Omega B}{2\pi} \cos \theta \]

\[ K = \frac{1}{c} \int [\mathbf{r} \times [\mathbf{J}_s \times \mathbf{B}]] \, dS \]

\[ W_{\text{tot}} = c \perp \frac{B_0^2 \Omega^4 R^6}{c^3} \left( \frac{\Omega R}{c} \right) i_A \]
Our predictions

If there are some restrictions on the longitudinal current

- narrow sheet $\Delta r \sim R_L/\lambda$
- effective particle acceleration up to $\Gamma \sim \sigma_M (10^6 \text{ for Crab})$
- transverse displacement $\Delta r \sim R_L/\lambda$
- Stop point!

Abrupt acceleration of a ‘cold’ ultrarelativistic wind from the Crab pulsar

F. A. Aharonian\textsuperscript{1,2}, S. V. Bogovalov\textsuperscript{3} & D. Khangulyan\textsuperscript{4}
Inner gap

Ruderman & Sutherland (1975)
Eidman et al (1975)

Mestel et al
PPdot – death line

Magnetars

Death line (RS!)
Rome (1973 – 1983)

Main results
• Neutron star is a radio pulsar if there is secondary electron-positron plasma generation near magnetic poles
• Arons model forever
• Main properties of the pulsar magnetosphere
• No magneto-dipole radiation

Problems
• Death line corresponds to RS model (shifted dipole? $n > 2$?)
• No self-consistent solution for the wind
• Alignment/counter-alignment
Dark ages (1983 – 1999)

• Kennel-Coroniti wind interaction with nebula
• Coroniti-Michel striped wind
• Michel dome
• GR effects are important (VB, Muslimov-Tsygan)
Coroniti-Michel stripped wind
Dome


J. Arons, A. Spitkosky (2002)
Dark ages (1983 – 1999)

Main results
• No results for pulsar magnetosphere
• Important steps in understanding the pulsar wind

Problems
• Ineffective particle acceleration (sigma-problem)
  \[ \Gamma \sim \sigma^{1/3} \]

• Contopoulos-Kazanas-Fendt numerical solution of pulsar equation (axisymmetric): disk, not GJ current
• Numerous confirmations
• Bogovalov force-free striped wind analytically
• Lyubarsky-Kirk striped wind reconnection

\[ -\left(1 - \frac{\Omega_F^2 \omega^2}{c^2}\right) \nabla^2 \Psi + \frac{2}{\omega} \frac{\partial \Psi}{\partial \omega} - \frac{16\pi^2}{c^2} I \frac{dI}{d\Psi} + \frac{\omega^2}{c^2} \left(\nabla \Psi \right)^2 \Omega_F \frac{d\Omega_F}{d\Psi} = 0 \]

A. Gruzinov (2005)  
S. Komissarov (2005)  
A. Timokhin (2005)
Analytical striped wind

\[ B_r = B_L \frac{R_L^2}{r^2} \Theta(\Phi), \]
\[ B_\varphi = -B_L \frac{R_L}{r} \sin \theta \Theta(\Phi), \]
\[ E_\theta = -B_L \frac{R_L}{r} \sin \theta \Theta(\Phi). \]

\[ \Phi = \cos \theta \cos \chi - \sin \theta \sin \chi \cos [\varphi - \Omega (t - r/c)] \]

\[ S \propto \sin^2 \theta \]
A Problem

A Problem

Arons, 1979

Main results

- There is universal axisymmetric solution (with definite charge and current density!)
- Equatorial current sheet, split-monopole, Y-point
- No magneto-dipole energy losses (both, in analytical and numerical solutions)

Problems

- Arons model and universal solution are in disagreement
- How to support the current (Mestel & Shibata, Beloborodov)?
Industrial revolution (2006 – 2012)

- Spitkovsky force-free inclined
- Princeton team MHD inclined
- First PIC inner gap simulations (Timokhin)
Inclined rotator


\[ W_{\text{tot}}^{(\text{MHD})} \approx \frac{1}{4} \frac{B_0^2 \Omega^4 R^6}{c^2} (1 + \sin^2 \chi) \]
Oppositely flowing currents can occupy the same open flux tube. Does this have any observational implications?

There is always a null-current field line in the open zone.
Inclined rotator

A. Tchekhovskoy,
A. Spitkovsky, J. Li,

I. Contopoulos et al
Inclined Rotator

Inclined Rotator

\( \chi = 60^\circ \)

Polar cap area


\[ \Phi_{\text{open}} \propto (1 + 0.2 \sin^2 \chi) \]

10% accuracy!
Wind

Figure 12. Colour-coded surface distribution of $B_r^2$ in the split-monopole solution (Bogovalov 1999). The current sheet, in which the radial magnetic field vanishes, describes the orientation of the current sheet in the numerical force-free solutions shown in Fig. 6.

Numerical force-free solution at $r = 6R_{1C}$:

Back to RS

Industrial revolution (2006 – 2012)

Main results

- There is universal inclined solution (with definite charge and current density!)
- No disagreement with the current model (but no confirmation!)
- No Michel-Bogovalov homogeneous wind
- Alignment for universal solution
- Back to Ruderman-Sutherland model (but time-dependent!)

Problems

- Sparking if there is not enough plasma
Modern time (2012 – …)

- PIC axysimmetric
- PIC inclined
- PIC reconnection
Particle in cell (PIC)

Cerutti B., A. Philippov, Parfrey K., Spitkovsky A.
Dome

S. Yuki, S. Shibata
PASJ, 64, 9 (2012)

A. Philippov, A. Spitkovsky
Modern time (2012 – …)

Main results
• Particle acceleration up to $\Gamma \sim \sigma_M$ outside the light cylinder
• Dome for small inclination
• GR effects help to produce relativistic wind

Problems
• It is necessary to create pairs OUTside the light cylinder
• No pure experiment
No pure experiment (braking index)

\[ n_{\text{br}} = \frac{\ddot{\Omega} \Omega}{\dot{\Omega}^2} \]

\[ n_{\text{br}}^{\text{VAC}} = 3 + 2 \tan^{-2} \chi \geq 3 \]

\[ n_{\text{br}}^{\text{MHD}} = 3 + 2 \frac{\sin^2 \chi \cos^2 \chi}{(1 + \sin^2 \chi)^2} \]

\[ 3 \leq n_{\text{br}}^{\text{MHD}} \leq 3.25 \]

\[ n_{\text{br}} = 1.93 + 1.5 \tan^2 \chi \]

No pure experiment (braking index)

\[ n_{\text{br}} = \frac{\ddot{\Omega} \Omega}{\dot{\Omega}^2} \]

No pure experiment (braking index)

\[ n_{br} = \frac{\ddot{\Omega} \Omega}{\dot{\Omega}^2} \]

Current losses

\[
I_r \dot{\Omega} = K_A^A + [K_A^A - K_A^\parallel] \sin^2 \chi,
\]

\[
I_r \Omega \dot{\chi} = [K_A^\perp - K_A^\parallel] \sin \chi \cos \chi.
\]

• One-to-one correspondence
  \(\chi\) evolves to 90 deg. if \(W_{\text{tot}}(0) > W_{\text{tot}}(90), n_{\text{br}} < 3\)
  \(\chi\) evolves to 0 deg. if \(W_{\text{tot}}(0) < W_{\text{tot}}(90), n_{\text{br}} > 3\)

• For BGI \(i_A \sim 1\)

• For Michel-Bogovalov \([K_A^{(A)} - K_A^{(A)}] = 0\)

• For Spitkovsky et al low the asymmetrical current is to be (much) larger than GJ one

\[
i_A > (\Omega R/c)^{-1}
\]
Conclusion

Wait a minute…