Pulsar magnetospheres and pulsar winds

V.S. Beskin

Lebedev Physical Institute

Moscow Institute of Physics and Technology

6 unpublished papers

VB, A.A.Philippov. "On the mean profiles of radio pulsars I: Theory of the propagation effects". MNRAS, **425**, 814-840 (2012)

VB,Ya.N.Istomin,A.A.Philippov, Radio pulsars: the search for truth. Physics Uspekhi, **56**, 164 (2014)

Ya. N.Istomin, A.A.Philippov, VB, On the collective curvature radiation. MNRAS, **422**, 23 (2014)

V.V.Prokofev, L.I.Arzamasskiy, VB. On the primary beam deceleration in the pulsar wind. MNRAS, **453**, 3540 (2015)

[1] P.Jaroenjittichai, A.A.Philippov, VB, M.Kramer. On the mean profiles of radio pulsars II: Identifying the mode

[2] VB, H.L.Hakobyan. On the mean profiles of radio pulsars III: New effects and reanalysis of individual pulsars

[3] L.I.Arzamasskiy, VB, S.T.Derry. On the statistics of interpulse radio pulsars

[4] L.I.Arzamasskiy, VB, V.V.Prokofev. On the internal structure of the current sheet in the pulsar wind

[5] VB, A.V.Chernoglazov, N.Zakamska. On the deceleration of relativistic jets in active galactic nuclei I: Radiation drag

[6] VB, E.E.Nokhrina. On the deceleration of relativistic jets in active galactic nuclei II: Particle loading

11 published papers (radio pulsars)

VB, A.A.Philippov. "On the mean profiles of radio pulsars I: Theory of the propagation effects". MNRAS, **425**, 814-840 (2012)

VB,Ya.N.Istomin,A.A.Philippov, Radio pulsars: the search for truth. Physics Uspekhi, **56**, 164 (2014)

Ya. N.Istomin, A.A.Philippov, VB, On the collective curvature radiation. MNRAS, **422**, 23 (2014)

V.V.Prokofev, L.I.Arzamasskiy, VB. On the primary beam deceleration in the pulsar wind. MNRAS, **453**, 3540 (2015)

[1] G.Li, A.Spitkovsky, A.Tchekhovskoy, ApJ, **746**, 12 (2012)

[2] G.Li, A.Spitkovsky, A.Tchekhovskoy, ApJ, **746**, L24 (2012)

[3] A.Tchekhovskoy, A.Spitkovsky,J.G,Li, MNRAS, **435**, L1 (2013)

[4] A.Philippov, A.Spitkovsky, ApJ, **785**, L33 (2014)

[5] A.Philippov, A.Tchekhovskoy, J.C.Li, MNRAS, **441**, 1879 (2014)

[6] B.Cerutti, A.Philippov, K.Parfrey, A.Spitkovsky, MNRAS, **448**, 606 (2015)

[7] A.A.Philippov, A.Spitkovsky, B.Cerutti, ApJ, 801, L19 (2015)

[8] L.Arzamasskiy, A.Philippov, A.Tchekhovsky, MNRAS, **453**, 3540 (2015)

[9] A.Philippov, B.Cerutti, A.Tchekhovskoy, A.Spitkovsky, ApJ, **815**, L19 (2015)

[10] B.Cerutti, A.Philippov, A.Spitkovsky, MNRAS, **457**, 2401 (2016)

[11] A.Tchekhovskoy, A.Philippov, A.Spitkovsky, MNRAS, **457**, 3384 (2016)

Several gaps

There are several gaps in radio pulsars:

Several gaps

There are several gaps in radio pulsars:

- inner gap

Several gaps

There are several gaps in radio pulsars:

- inner gap,
- outer gap

Several gaps

There are several gaps in radio pulsars:

- inner gap,
- outer gap,
- slot gap

Several gaps

There are several gaps in radio pulsars:

- 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.

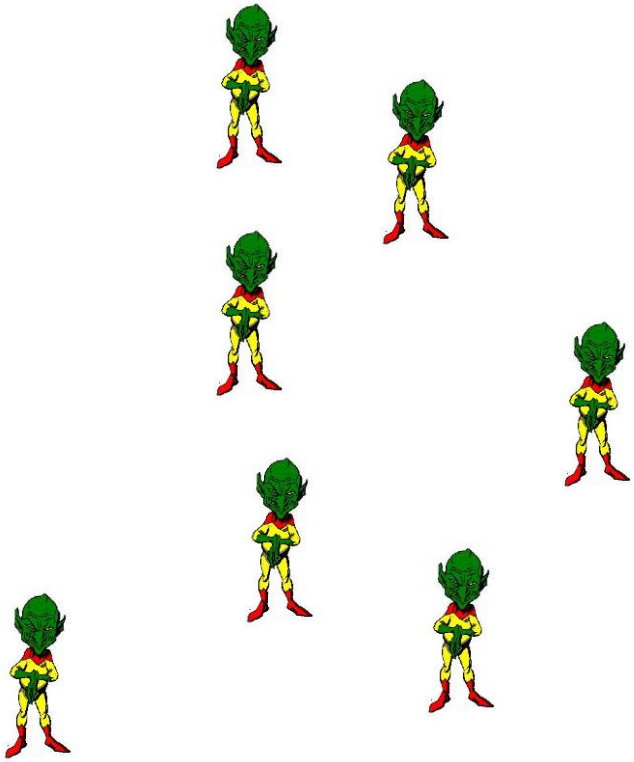
Let us return to the very ground…

- What we know definitely?
- Are we sure?

I.S.Shklovsky
(1916-1985)

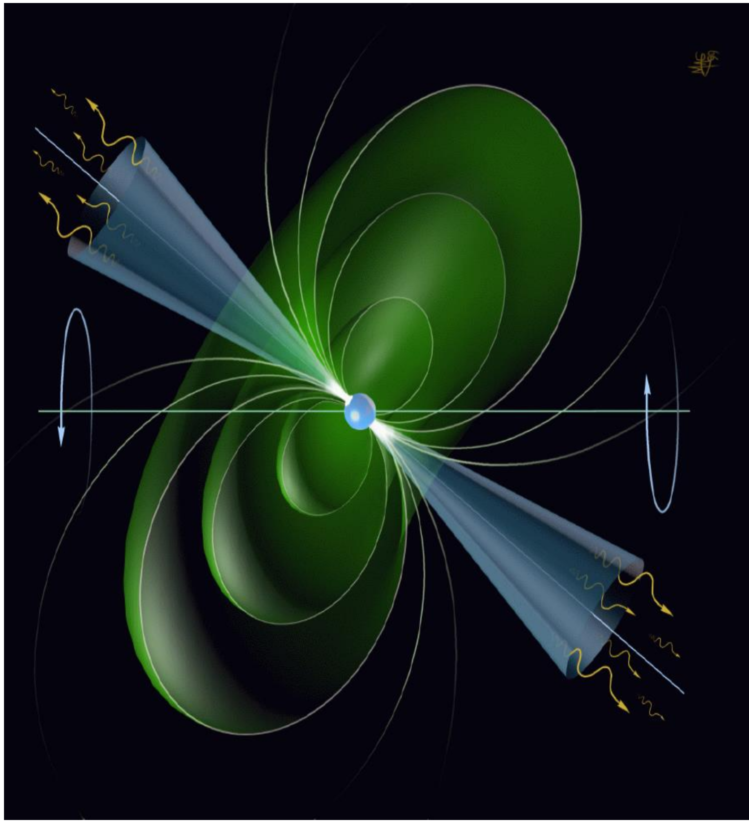
V.L.Ginzburg
(1916-2009)

Ya.B.Zeldovich
(1914-1987)



Radio pulsars – rotating solitary* neutron stars

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



Everything is clear?

- Mechanism of the coherent radio emission.
- NS works as PSR for both orientation of $\boldsymbol{\Omega}$ and $\boldsymbol{m}$, or for only one (which?)
- Neutron star radius $\boldsymbol{R}$?
- $\boldsymbol{B} \sim 10^{12}$ G?
  Up to $\boldsymbol{B} \sim 10^{15}$ 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 se[illegible]NS as [illegible] for both [illegible]tatio[illegible] and $\boldsymbol{m}$, or for only one [illegible]ch?)
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- Electron-positron plasma?
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- Outer gap – does it exist?

Pulsar chronology

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

Hellas (1967 – 1973)

- Key electrodynamical idea
- Goldreich-Julian charge density

$$\rho_{\rm GJ} = -\frac{\mathbf{\Omega}\cdot\mathbf{B}}{2\pi c}$$

- Michel magnetization parameter

  (maximum bulk Lorentz-factor)

$$\sigma = \frac{\Omega^2\Psi_{\rm tot}}{8\pi^2 c^2 \mu\eta}$$

- Sturrock (multiplicity parameter)

$$\gamma + B \rightarrow e^+ + e^- + B$$

$$\lambda = \frac{n^{\rm (lab)}}{n_{\rm GJ}}$$

- Radhakrishnan-Cooke RVM ('hollow cone' model)

Hellas (1967 – 1973)

- Key electrodynamical idea
- Goldreich-Julian charge density

$$\rho_{\rm GJ} = -\frac{\mathbf{\Omega}\cdot\mathbf{B}}{2\pi c}$$

and current density (!)

$$j_{\rm GJ} = \rho_{\rm GJ} c$$

- Michel magnetization parameter

$$\sigma = \frac{\Omega^2 \Psi_{\rm tot}}{8\pi^2 c^2 \mu \eta}$$

(maximum bulk Lorentz-factor)

- Sturrock (multiplicity parameter)

$$\lambda = \frac{n^{\rm (lab)}}{n_{\rm GJ}}$$

$$\gamma + B \rightarrow e^{+} + e^{-} + B$$

- Radhakrishnan-Cooke RVM (‘hollow cone’)

The key electrodynamic idea

(N.S.Kardashev,1964; F.Pacini, 1967)

Magneto-dipole (vacuum) radiation

$$W_{\rm tot} = -J_{\rm r}\Omega\dot{\Omega} \approx \frac{1}{6}\frac{B_0^2\Omega^4R^6}{c^3}\sin^2\chi$$

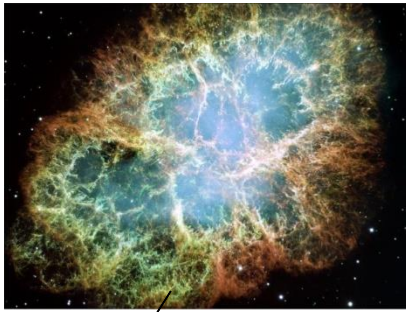
$$W_{\rm tot} \sim 10^{32}\ \text{erg/s}$$

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



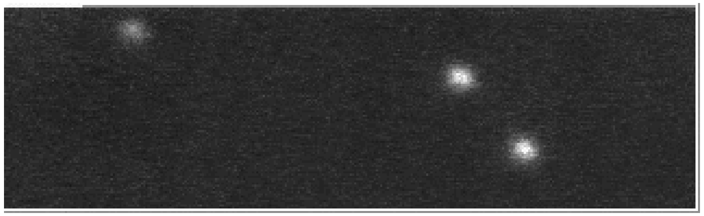
$$P = 0.033 \text{ s},$$

$$\mathrm{d}P/\mathrm{d}t = 4\ 10^{-13}$$

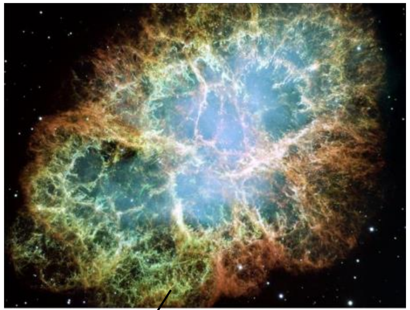
Full energy loss $W_{\mathrm{tot}} = -I_r\,\Omega\,\mathrm{d}\Omega/\mathrm{d}t \sim 5\ 10^{38}$ erg/s

The life time $\tau = P/(\mathrm{d}P/\mathrm{d}t) \sim 1000$ years

Detection of optical pulsations



The key electrodynamic idea



The moment of the truth – Crab pulsar

$$P = 0.034 \text{ s},$$

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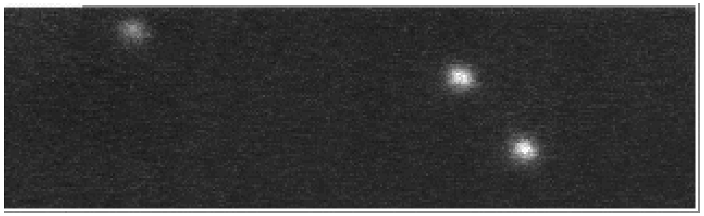
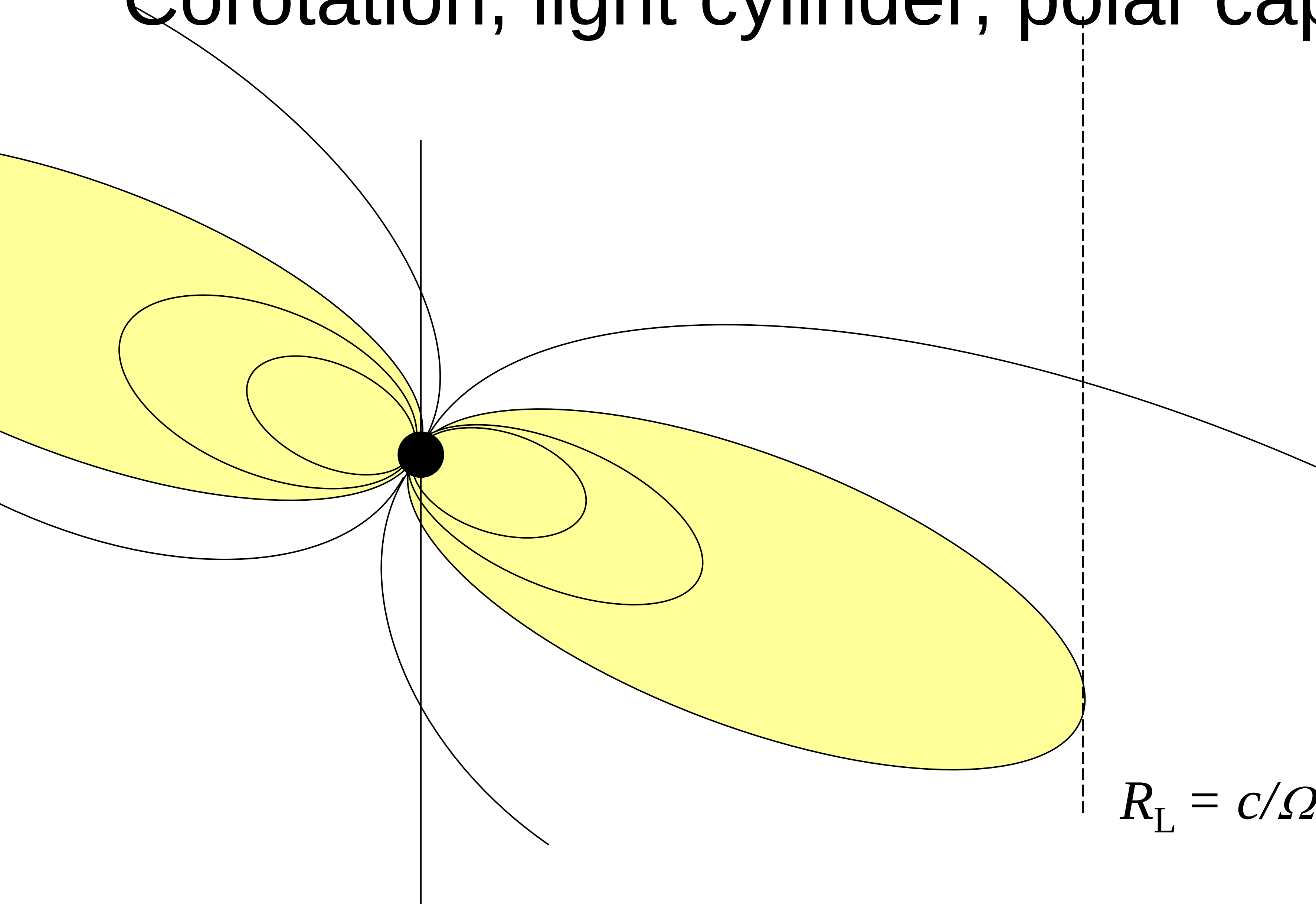
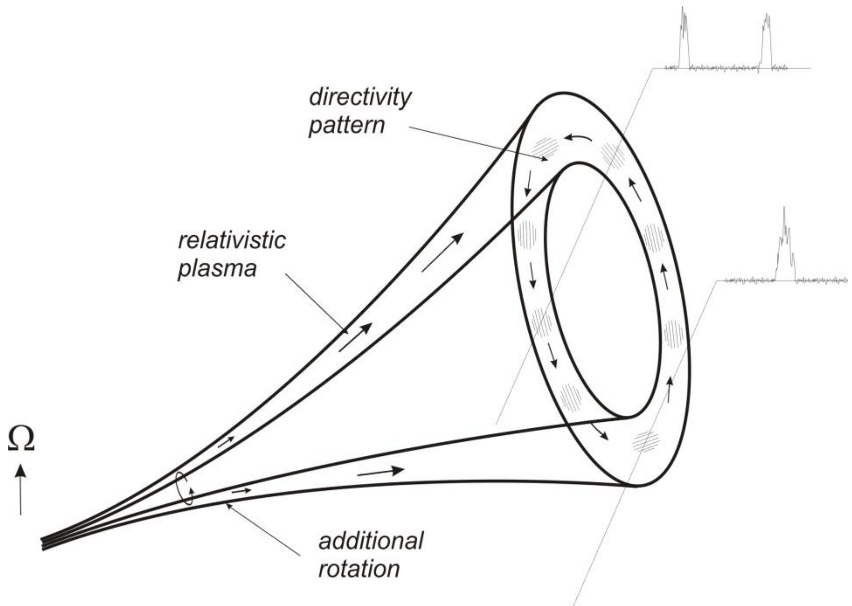


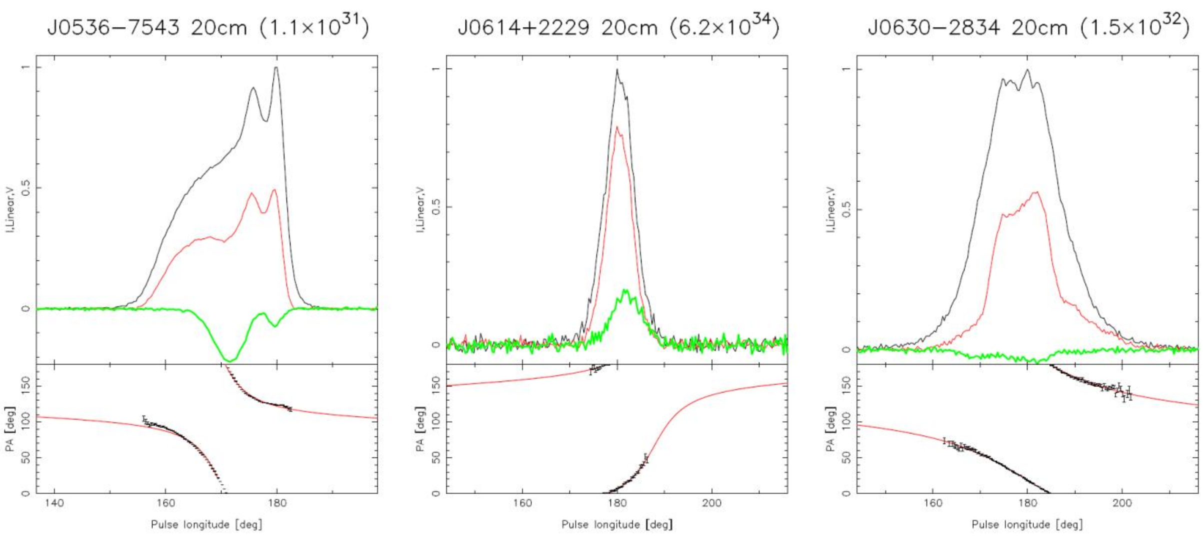
Corotation, light cylinder, polar cap



“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-Sutherlend gap (no injection from the surface)
- Arons gap (free escape)
- BGI – full screening of the magneto-dipole radiation
- BGI – possibility of a domain with $\boldsymbol{E} > \boldsymbol{B}$

Force-free approximation

One can neglect energy of particles

$$\frac{1}{c}\mathbf{j} \times \mathbf{B} + \rho_{\mathrm{e}}\mathbf{E} = 0$$

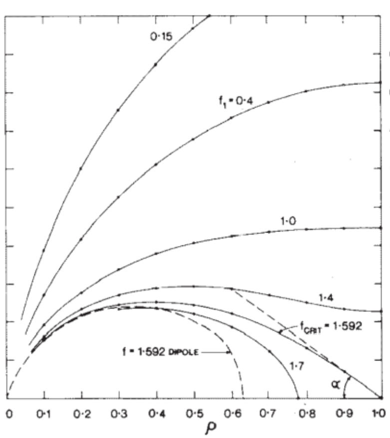
Pulsar equation

$$-\left(1 - \frac{\Omega_{\mathrm{F}}^2 \varpi^2}{c^2}\right) \nabla^2 \Psi + \frac{2}{\varpi}\frac{\partial \Psi}{\partial \varpi} - \frac{16\pi^2}{c^2} I \frac{\mathrm{d}I}{\mathrm{d}\Psi} + \frac{\varpi^2}{c^2} \left(\nabla \Psi\right)^2 \Omega_{\mathrm{F}} \frac{\mathrm{d}\Omega_{\mathrm{F}}}{\mathrm{d}\Psi} = 0$$

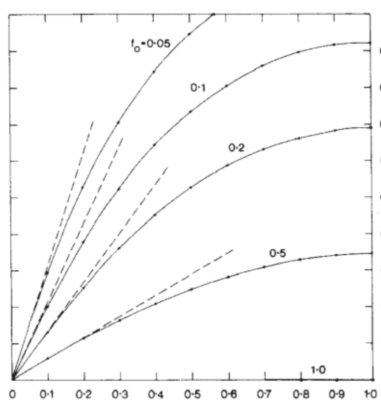
(Michel 1973, Mestel 1993, Scharlemann & Wagoner 1973,
Okamoto 1974, Mestel & Wang 1979)

First solutions

$$-\left(1-\frac{\Omega_{\rm F}^2\varpi^2}{c^2}\right)\nabla^2\Psi+\frac{2}{\varpi}\frac{\partial\Psi}{\partial\varpi}-\frac{16\pi^2}{c^2}I\frac{{\rm d}I}{{\rm d}\Psi}+\frac{\varpi^2}{c^2}\left(\nabla\Psi\right)^2\Omega_{\rm F}\frac{{\rm d}\Omega_{\rm F}}{{\rm d}\Psi}=0$$



F. Michel (1973)



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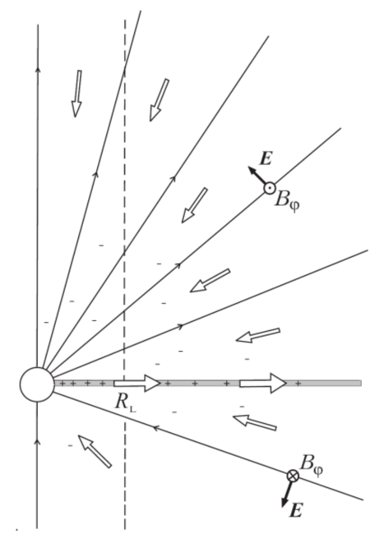

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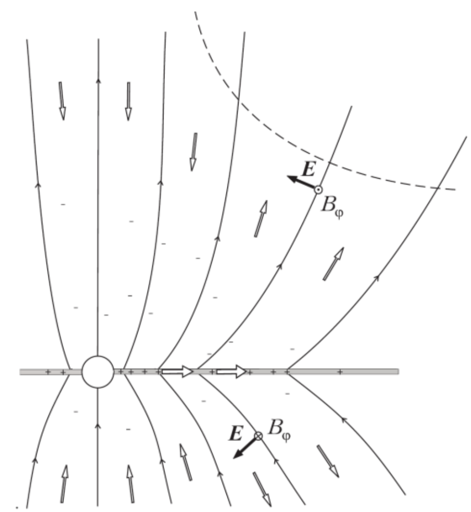
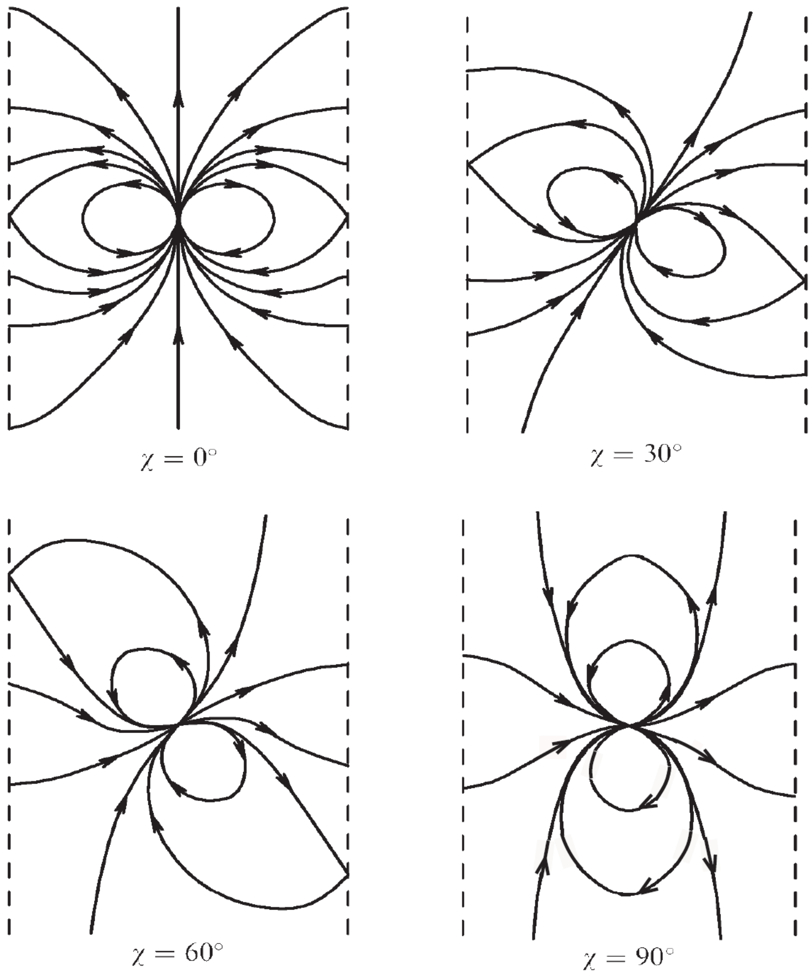
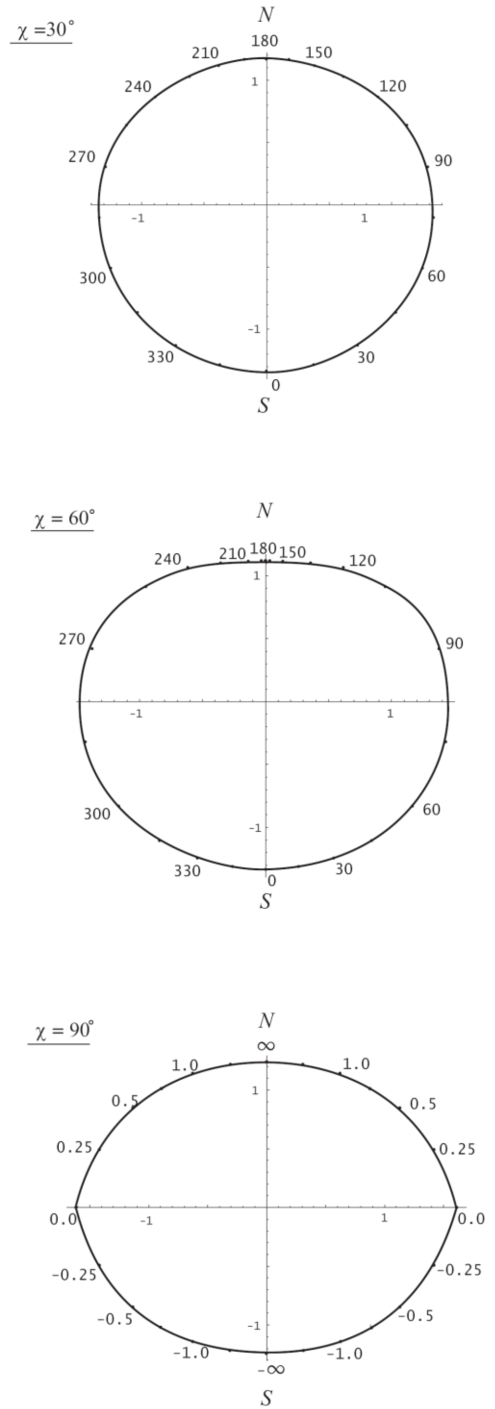


R.Blandford (1976)

Incline rotator, $I = 0$

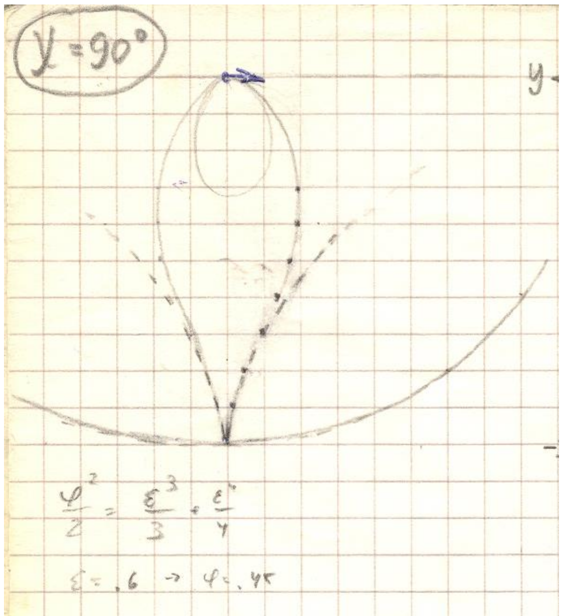


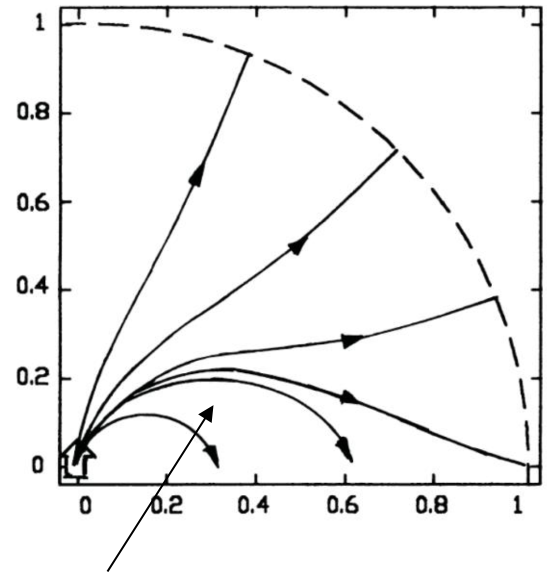


VB, A.V.Gurevich & Ya.N.Istomin JETP, **85,** 235 (1983)

Orthogonal Rotator, $I = 0$

VB, A.V.Gurevich, Ya.N.Istomin, JETP, **58**, 235 (1983)
L.Mestel, P.Panagi, S.Shibata, MNRAS, **309**, 388 (1999)





Equatorial plane

No energy flux through the light cylinder

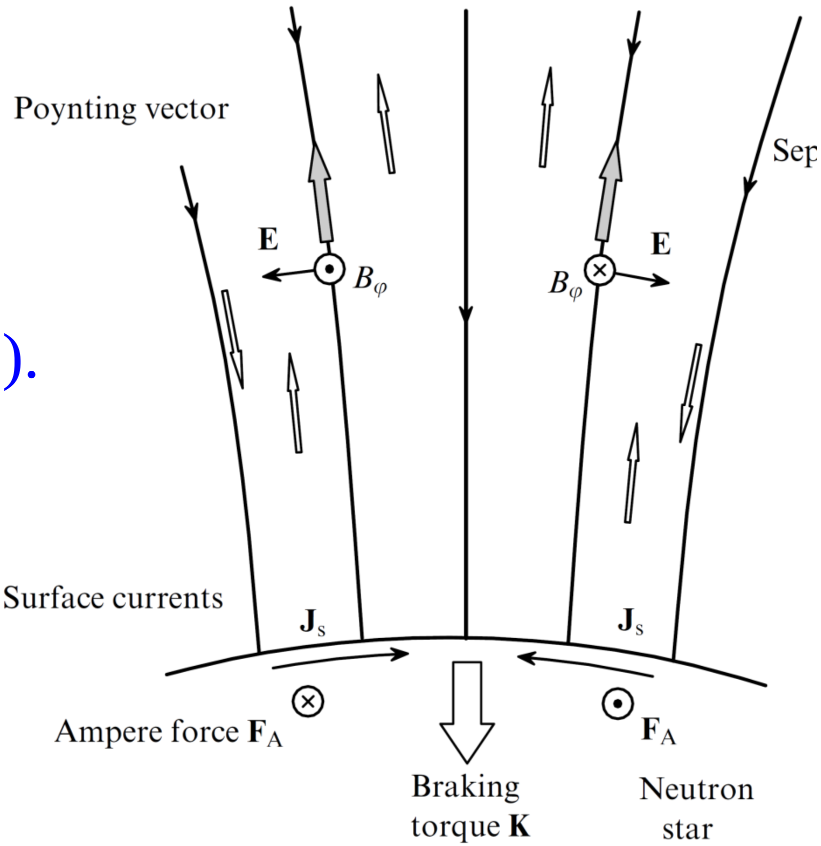
$$B_\varphi \propto (1 - x_r^2)^2$$

Current losses

For current loss mechanism is necessary to have

- Plasma in the magnetosphere,
- regular poloidal magnetic field,
- rotation (inductive electric field ***E*,**
  EMF δU),
- longitudinal current I
  (toroidal magnetic field ***B***).

$$W_{\rm tot} = I\delta U$$



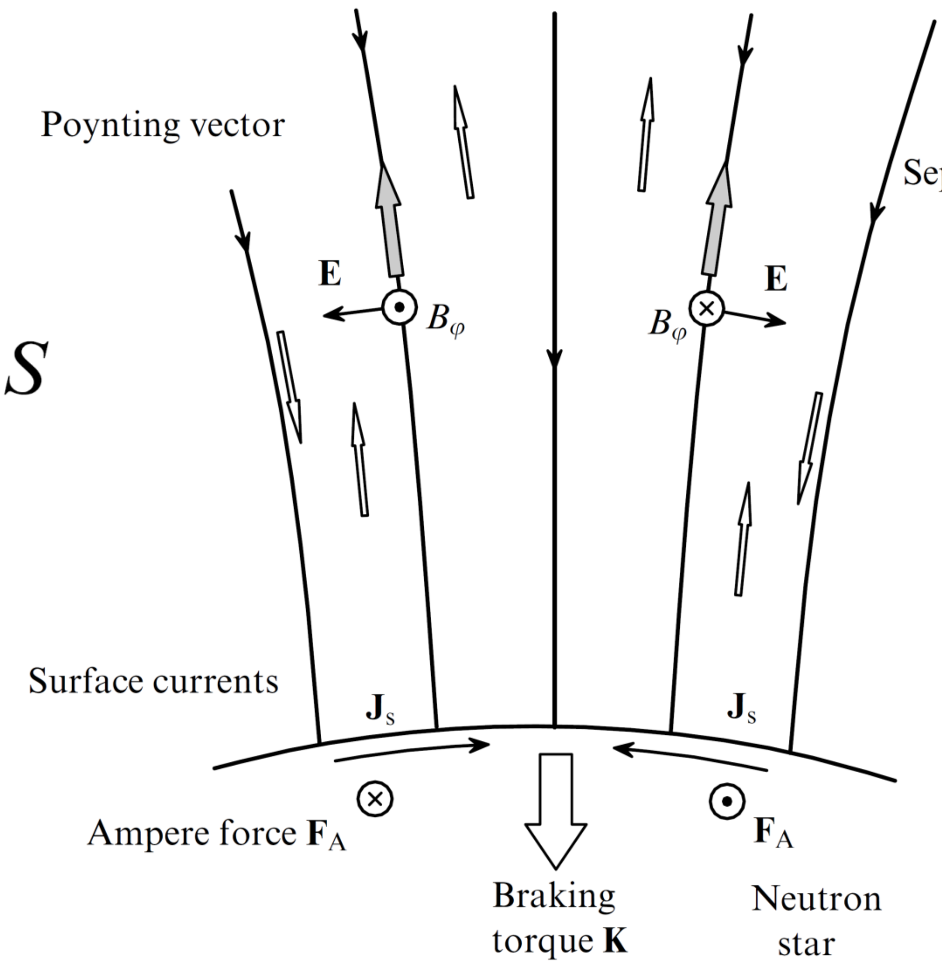
Current losses

$$W_{\rm tot} = -\boldsymbol{\Omega} \cdot \mathbf{K}$$

$$\mathbf{K} = \frac{1}{c} \int \left[\mathbf{r} \times [\mathbf{J}_{\rm s} \times \mathbf{B}]\right] \mathrm{d}S$$

$$\nabla_2 \mathbf{J}_{\rm s} = j_{\rm n}$$

$$\mathbf{J}_{\rm s} = \frac{I}{2\pi R \sin\theta} \mathbf{e}_\theta$$



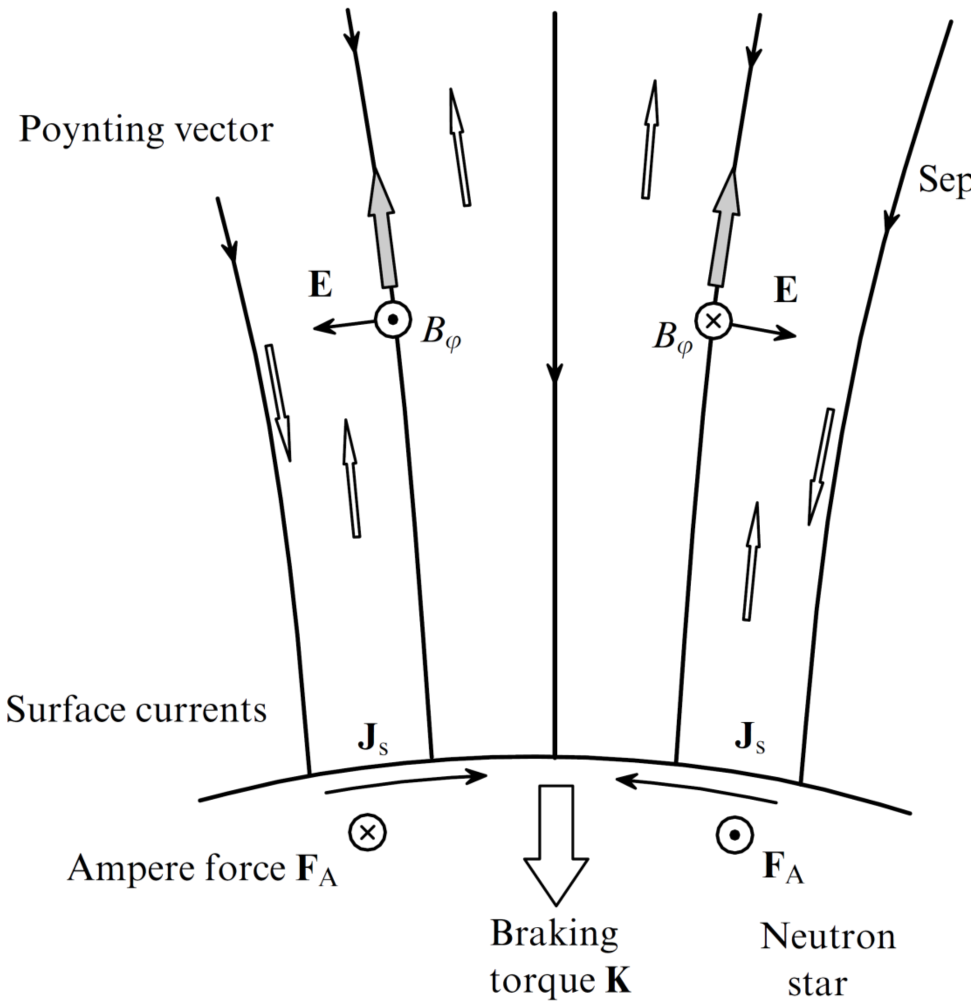
Current losses

$$W_{\rm tot} = c_{\parallel}\frac{B_0^2\Omega^4R^6}{c^3}i_0$$

$$i_0 = j_{\parallel}/j_{\rm GJ}$$

$$W_{\rm tot}^{\rm (BGI)} \approx i_{\rm s}^{\rm A}\,\frac{B_0^2\Omega^4R^6}{c^2}\,\cos^2\chi$$

for GJ current (BGI)

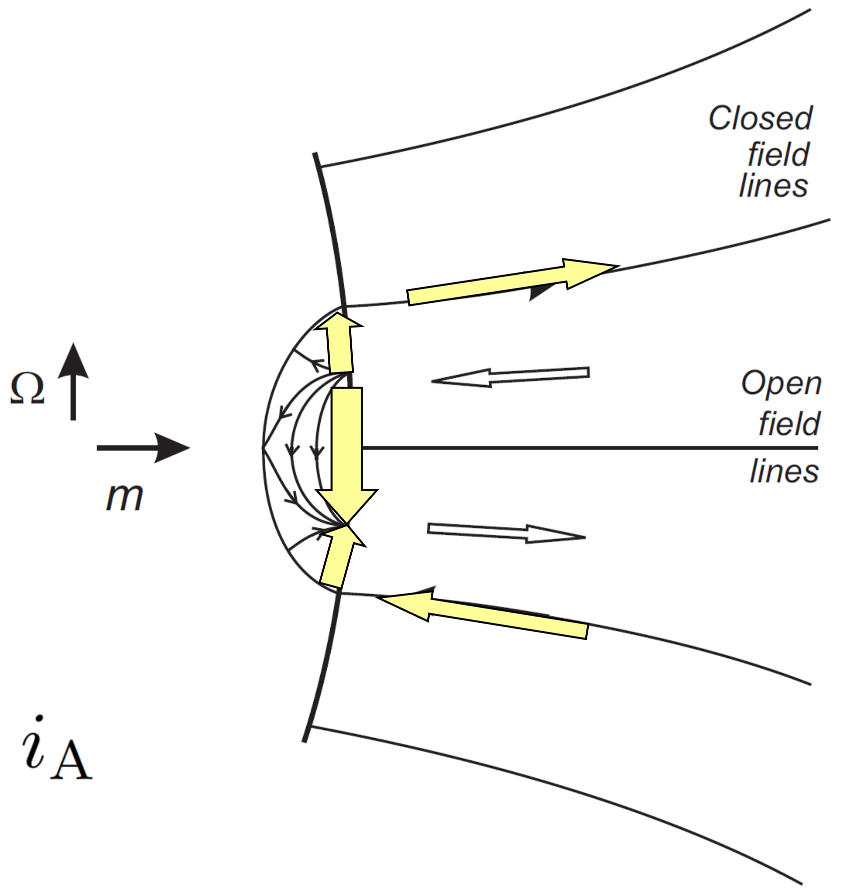


Orthogonal rotator

VB, A.V.Gurevich, Ya.N.Istomin JETP **58**, 235 (1983)

$$j_{\rm GJ} \approx \frac{\Omega B}{2\pi} \cos \theta$$

$$\mathbf{K} = \frac{1}{c} \int \left[\mathbf{r} \times [\mathbf{J}_{\rm s} \times \mathbf{B}]\right] {\rm d}S$$

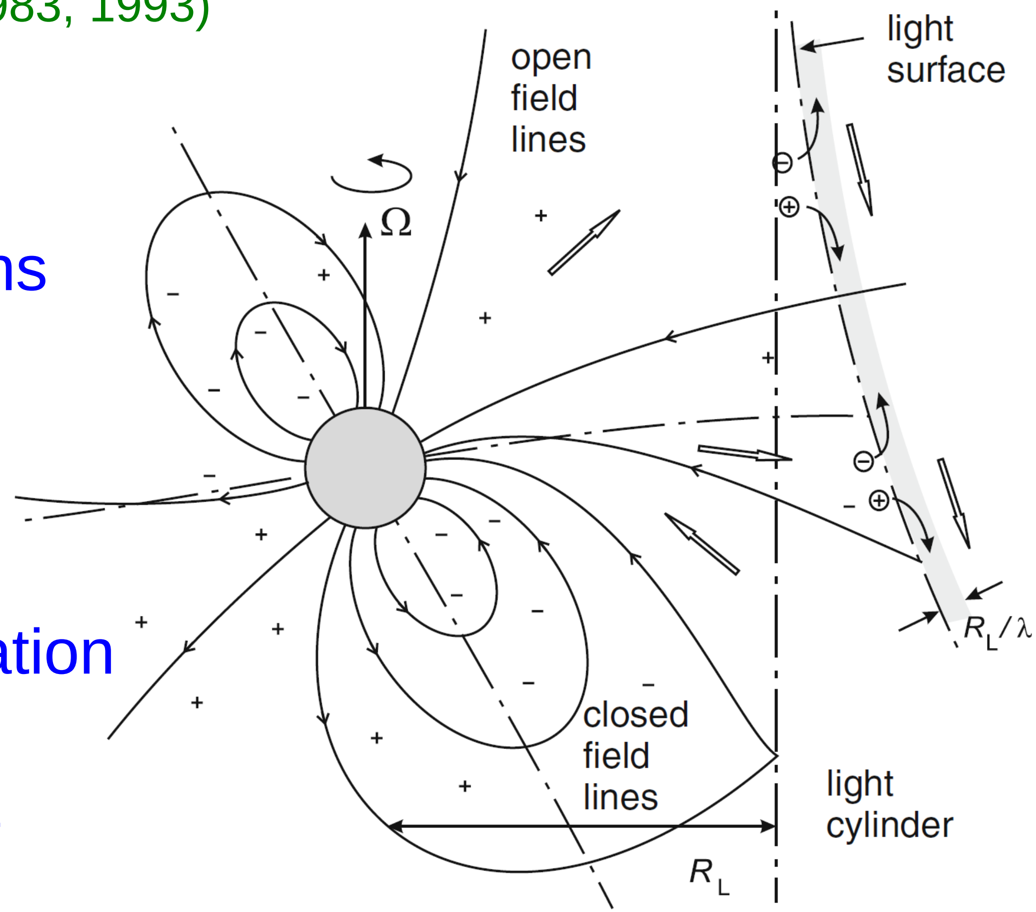


$$W_{\rm tot} = c_{\perp} \frac{B_0^2 \Omega^4 R^6}{c^3} \left(\frac{\Omega R}{c}\right) i_{\rm A}$$

$i_A = j_\parallel / \rho_{GJ} c$

Our predictions

VB, Ya.N.Istomin, A.V.Gurevich (1983, 1993)
VB, R.R.Rafikov (2000)



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 for Crab)

- transverse displacement

$\Delta r \sim R_L/\lambda$

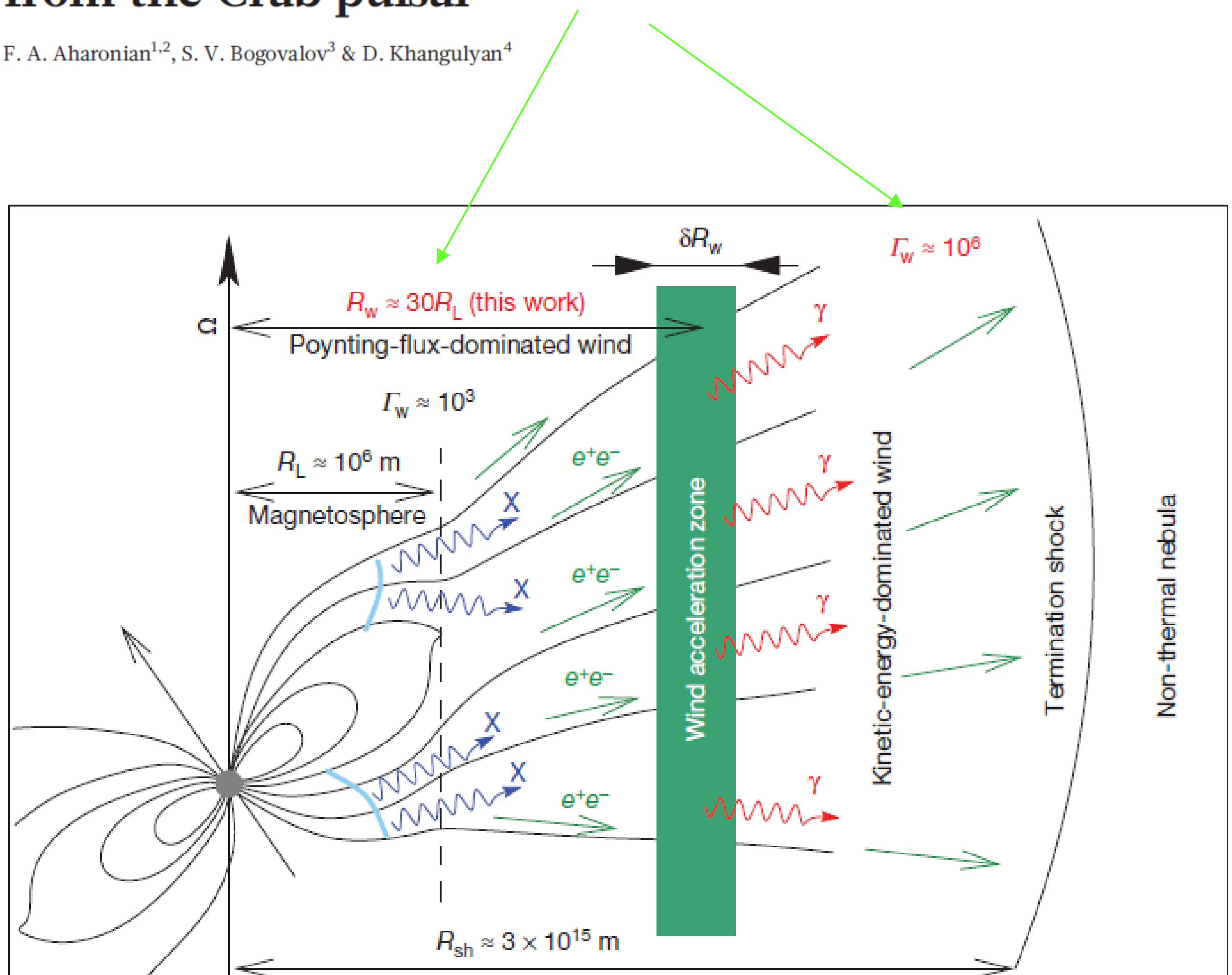
- Stop point!

LETTER

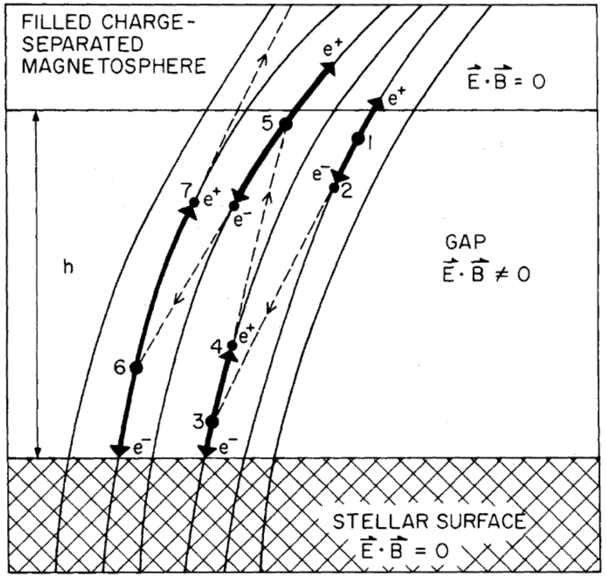
doi:10.1038/nature10793

Abrupt acceleration of a 'cold' ultrarelativistic wind from the Crab pulsar

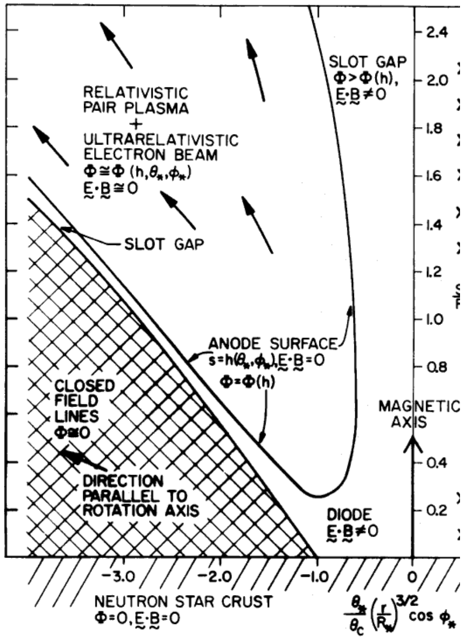
F. A. Aharonian[1,2], S. V. Bogovalov[3] & D. Khangulyan[4]



Inner gap

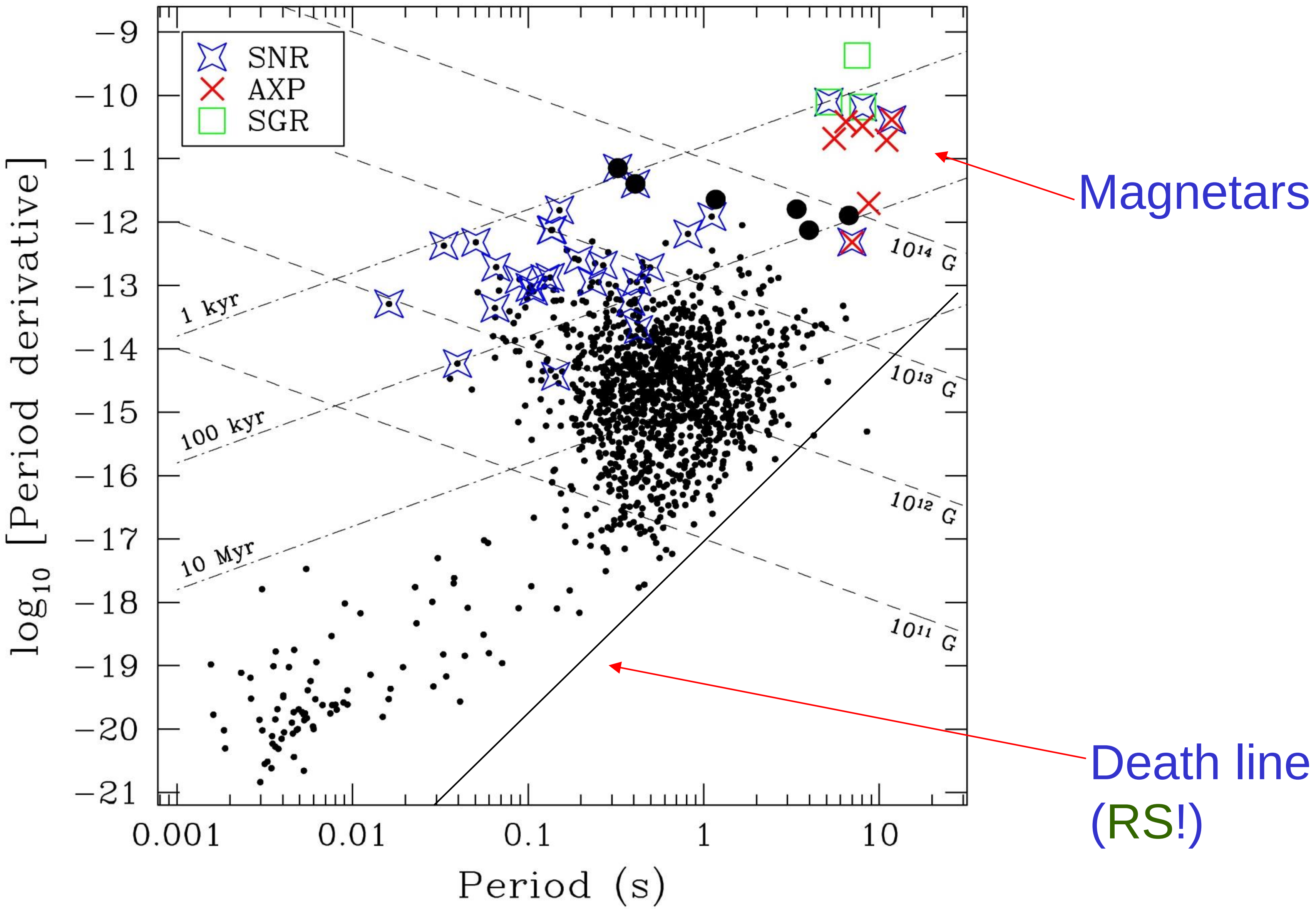


Ruderman & Sutherland (1975)
Eidman et al (1975)



Arons et al (1977-1981)
Mestel et al

PPdot – death line



Rome (1973 – 1983)

Main results

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

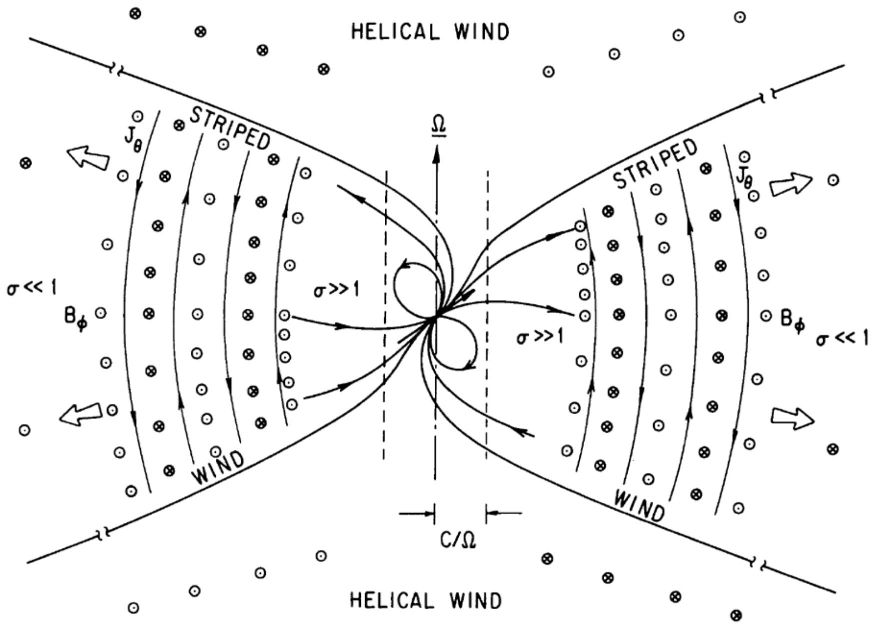
Problems

- Death line corresponds to RS model (shifted dipole? $n > 2$?)
- No self-consistent solution for the wind
- Alignment/counter-alignment

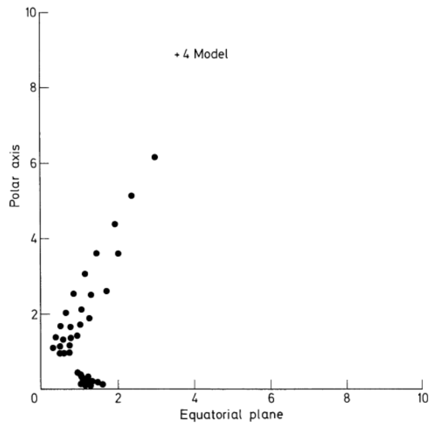
Dark ages (1983 – 1999)

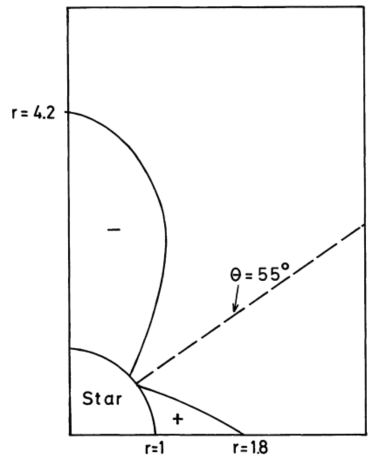
- Kennel-Coroniti wind interaction with nebula
- Coroniti-Michel striped wind
- Michel dome
- GR effects are important (VB, Muslimov-Tsygan)

Coroniti-Michel stripped wind

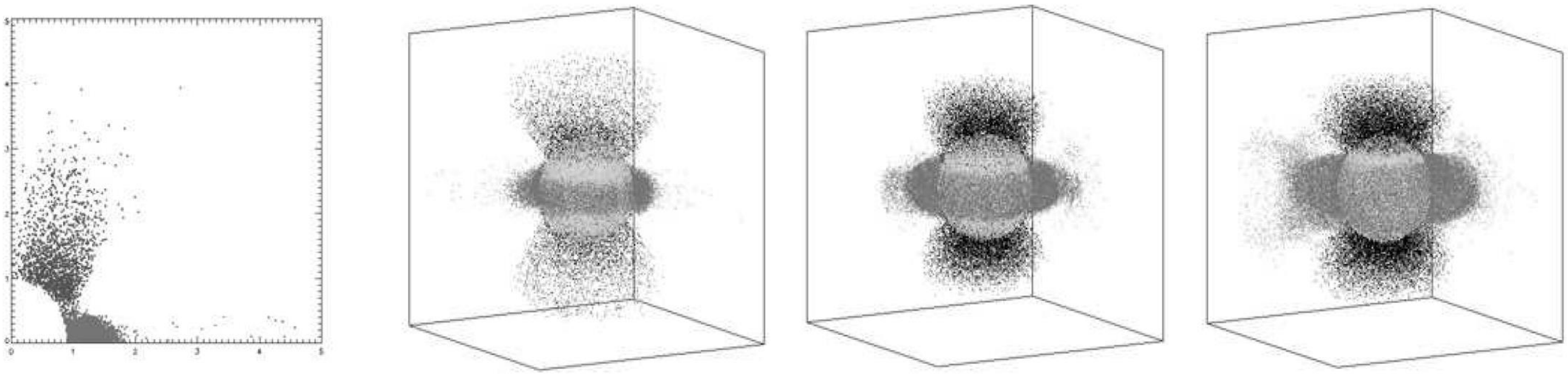


Dome





J.Krause-Polstorff, F.C.Michel, A&A **144**, 72 (1985)



J.Arons, A.Spitkosky (2002)

Dark ages (1983 – 1999)

Main results

- No results for pulsar magnetosphere
- Important steps in undertanding the pulsar wind

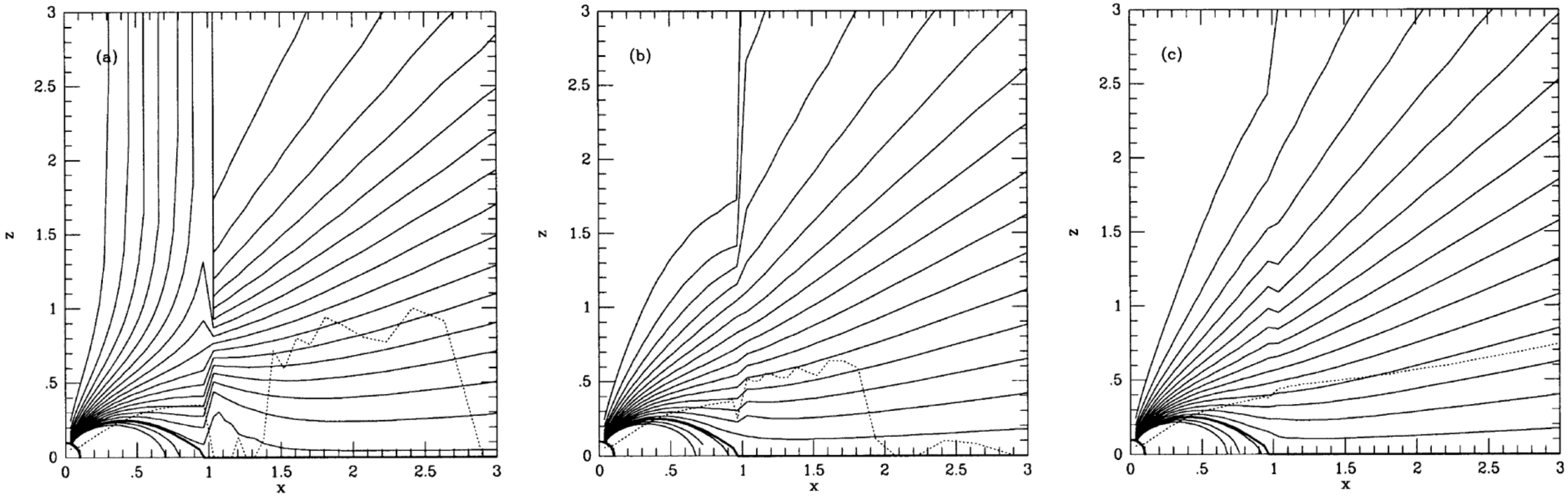
Problems

- Ineffective particle acceleration (sigma-problem)

$$\Gamma \sim \sigma^{1/3}$$

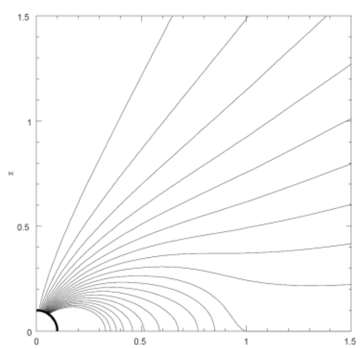
Renaissance (1999 – 2006)

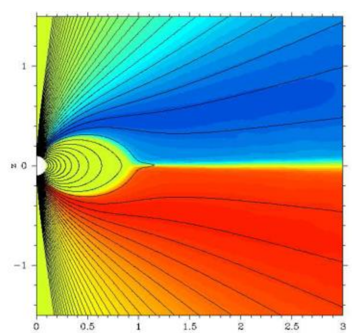
- Contopoulos-Kazanas-Fendt numerical solution of pulsar equation (axisymmetric): disk, not GJ current
- Numerous confirmations
- Bogovalov force-free striped wind analytically
- Lyubarsky-Kirk striped wind reconnection

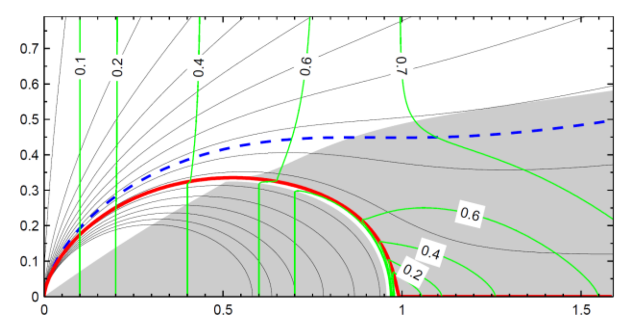


I.Contopoulos, D.Kazanas & Ch.Fendt, ApJ, **511**, 351 (1999)

$$-\left(1-\frac{\Omega_{\mathrm{F}}^{2}\varpi^{2}}{c^{2}}\right)\nabla^{2}\Psi+\frac{2}{\varpi}\frac{\partial\Psi}{\partial\varpi}-\frac{16\pi^{2}}{c^{2}}I\frac{\mathrm{d}I}{\mathrm{d}\Psi}+\frac{\varpi^{2}}{c^{2}}\left(\nabla\Psi\right)^{2}\Omega_{\mathrm{F}}\frac{\mathrm{d}\Omega_{\mathrm{F}}}{\mathrm{d}\Psi}=0$$







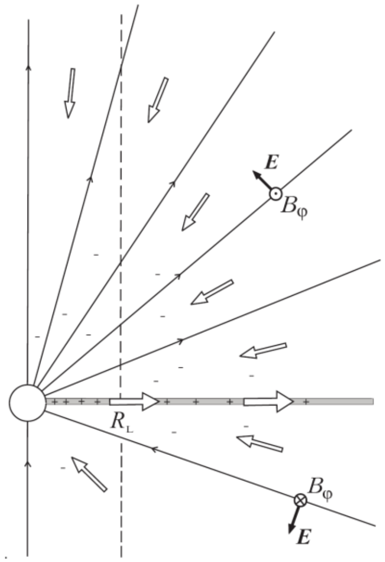
A.Gruzinov (2005)

S.Komissarov (2005)

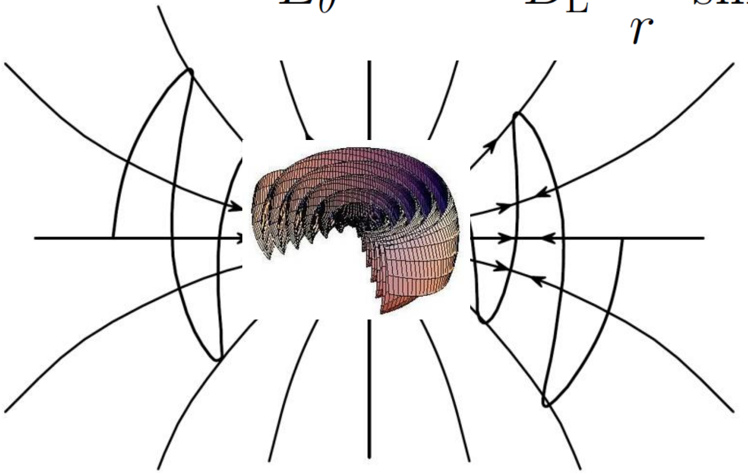
A.Timokhin (2005)

Analytical striped wind

$$
\begin{aligned}
B_r &= B_{\rm L}\,\frac{R_{\rm L}^2}{r^2}\,\Theta(\Phi),\\
B_\varphi &= -B_{\rm L}\,\frac{R_{\rm L}}{r}\,\sin\theta\,\Theta(\Phi),\\
E_\theta &= -B_{\rm L}\,\frac{R_{\rm L}}{r}\,\sin\theta\,\Theta(\Phi).
\end{aligned}
$$



F.C.Michel (1973)

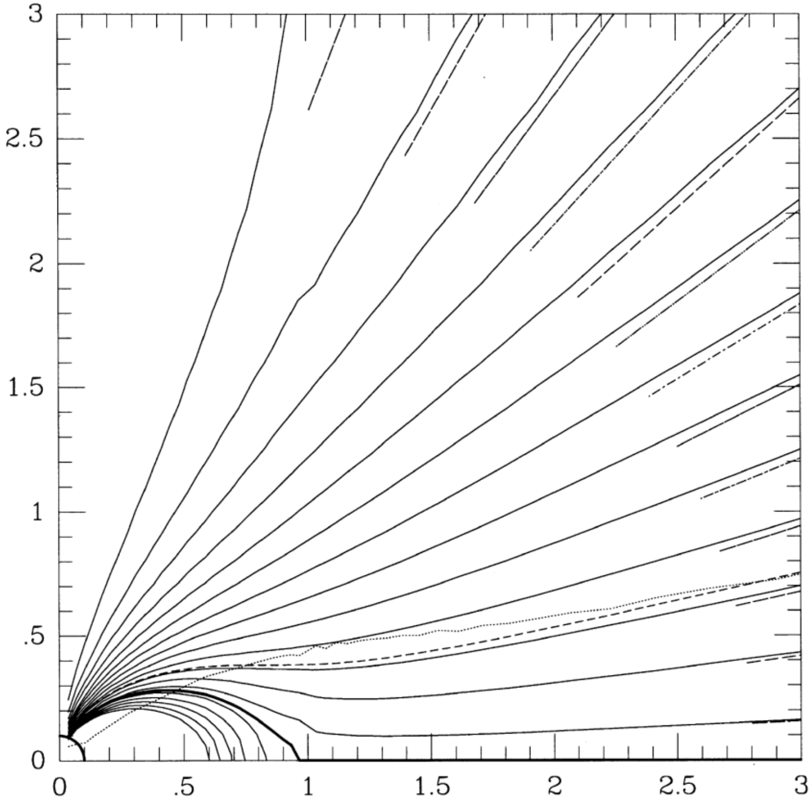


S.V.Bogovalov (1999)

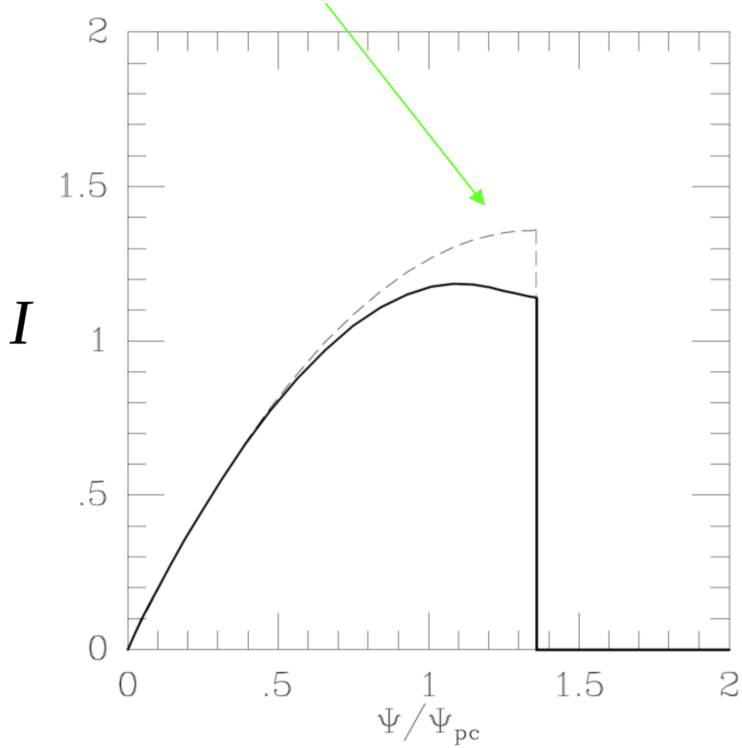
$$\Phi = \cos\theta\cos\chi - \sin\theta\sin\chi\cos\left[\varphi - \Omega\left(t - r/c\right)\right]$$

$$S \propto \sin^2\theta$$

A Problem

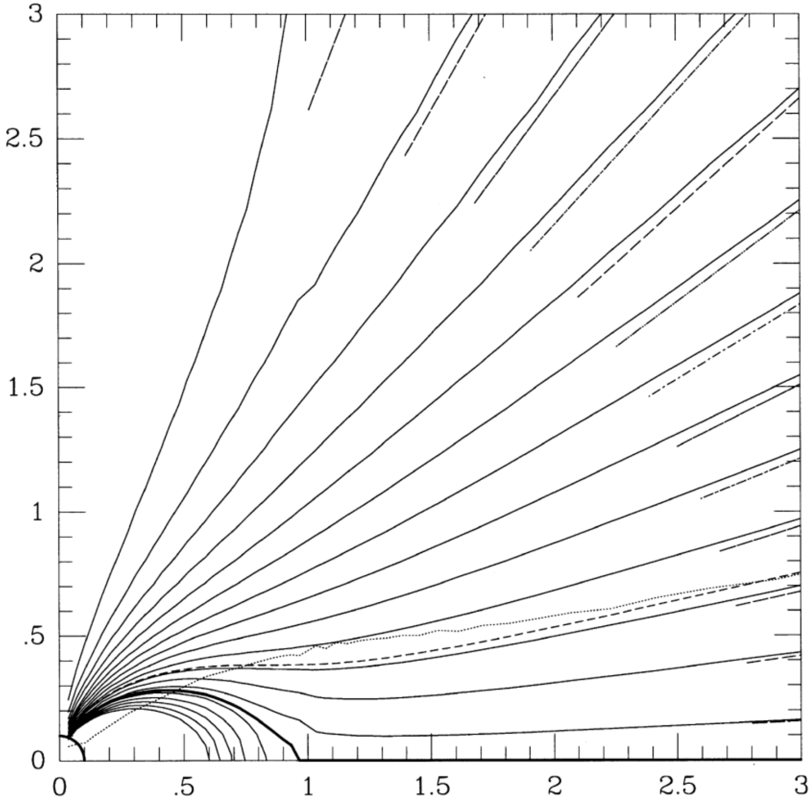


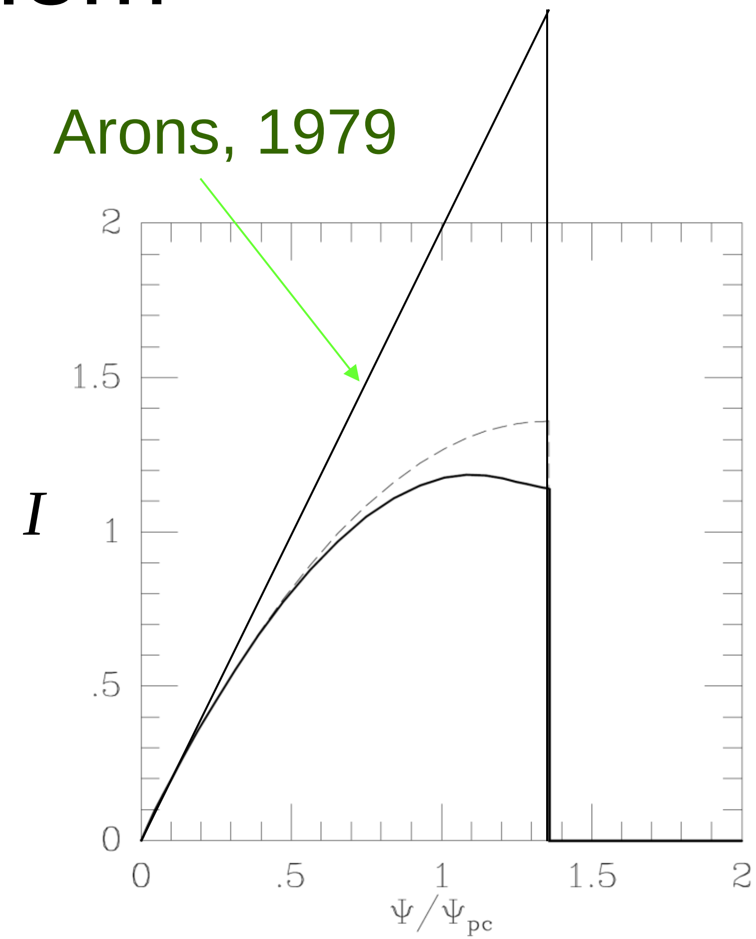
Michel, 1973



I.Contopoulos, D.Kazanas & Ch.Fendt,
ApJ, **511**, 351 (1999)

A Problem





I.Contopoulos, D.Kazanas & Ch.Fendt,
ApJ, **511**, 351 (1999)

Renaissance (1999 – 2006)

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)

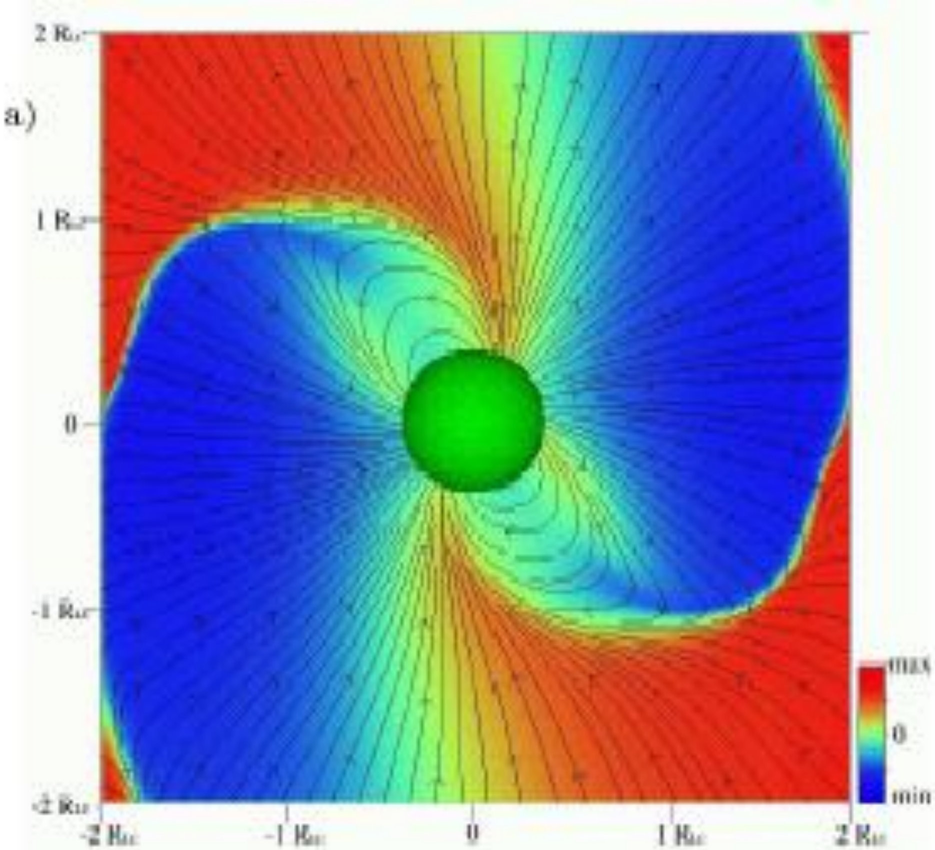
- Spitkovsky force-free inclined
- Princeton team MHD inclined
- First PIC inner gap simulations (Timokhin)

Inclined rotator

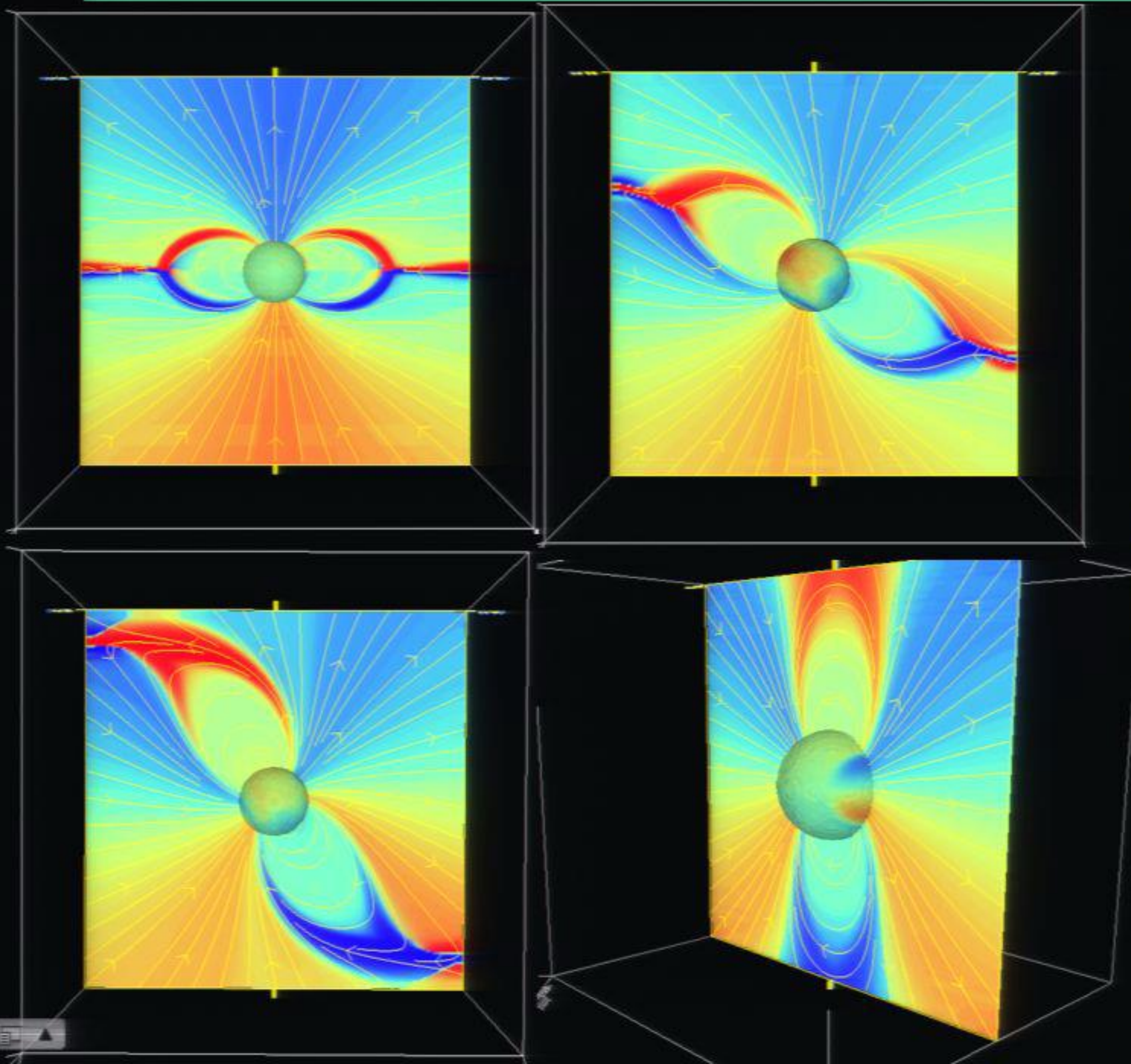
A.Spitkovsky, ApJ Lett., **648**, L51 (2006)

$$W_{\rm tot}^{\rm (MHD)} \approx \frac{1}{4}\frac{B_0^2\Omega^4 R^6}{c^2}(1+\sin^2\chi)$$

a)



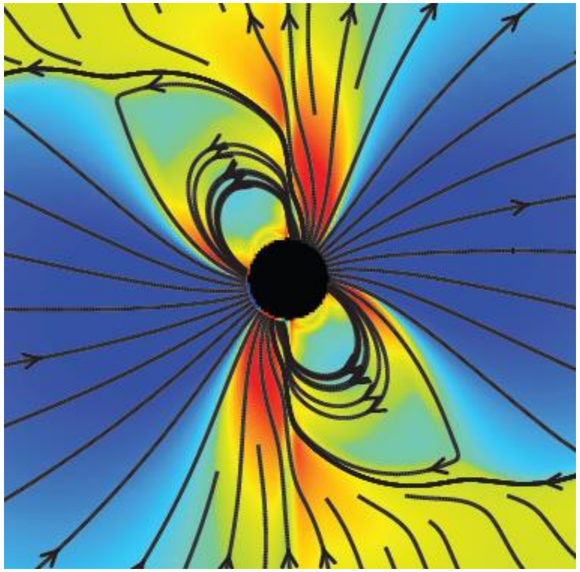
Magnetospheric currents

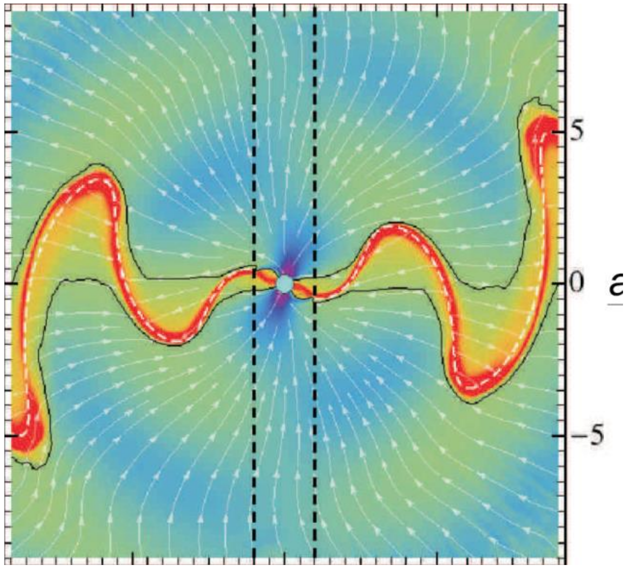


Oppositely flowing currents can occupy the same open flux tube. Does this have any obervational implications?

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

Inclined rotator

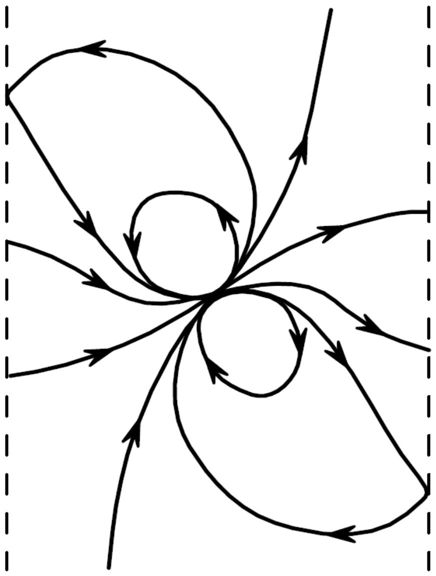




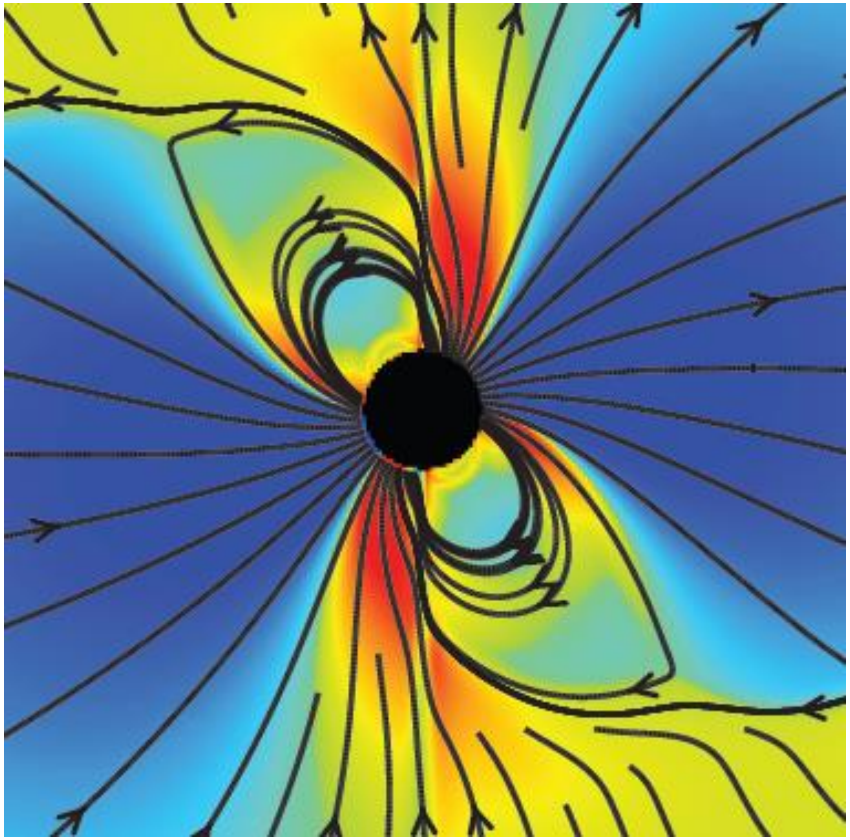
A.Tchekhovskoy,
A.Spitkovsky, J.Li,
MNRAS, **431**, 1 (2013)

I.Contopoulos et al

Inclined Rotator

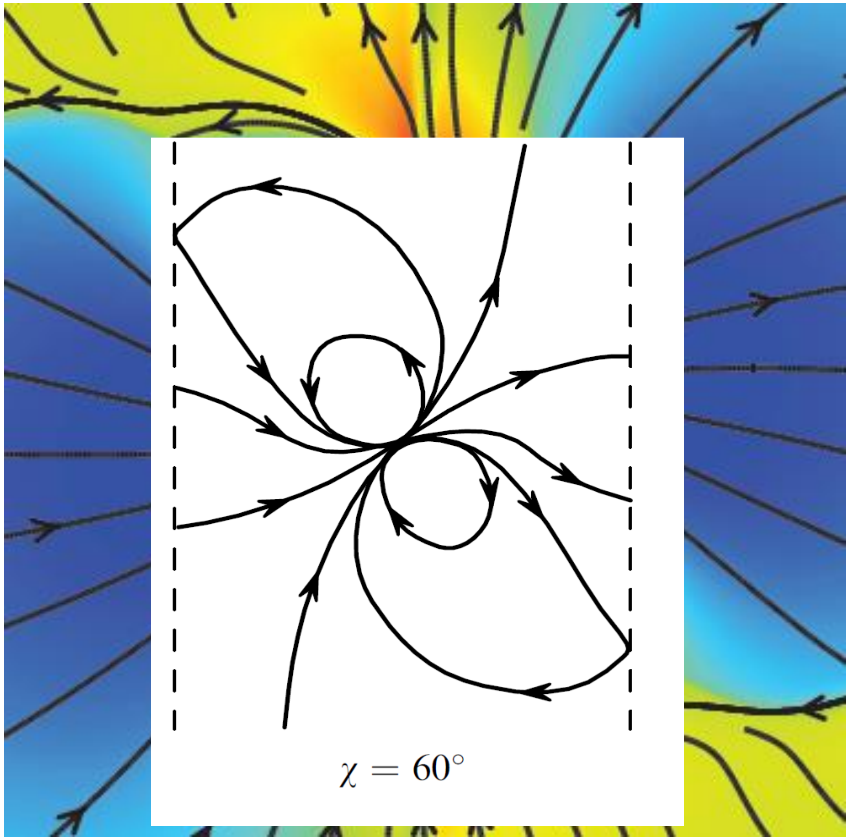


$\chi = 60^\circ$



A.Tchekhovskoy,
A.Spitkovsky, J.Li,
MNRAS, **431**, 1 (2013)

Inclined Rotator



A.Tchekhovskoy,
A.Spitkovsky, J.Li,
MNRAS, **431**, 1 (2013)

Polar cap area

VB, A.V.Gurevich, Ya.N.Istomin,
Physics of the pulsar magnetosphere
(1993)

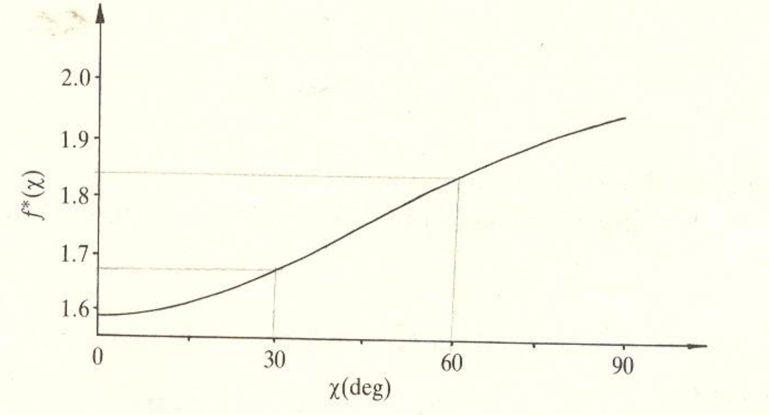


Fig. 4.12. Dependence of the parameter $f^*(\chi)$ on the angle χ.

A.Tchekhovskoy, A.Philippov, A.Spitkovsky, MNRAS, **457**, 3384 (2016)

$$\Phi_{\rm open} \propto (1 + 0.2\sin^2\chi)$$

10% accuracy!

Wind

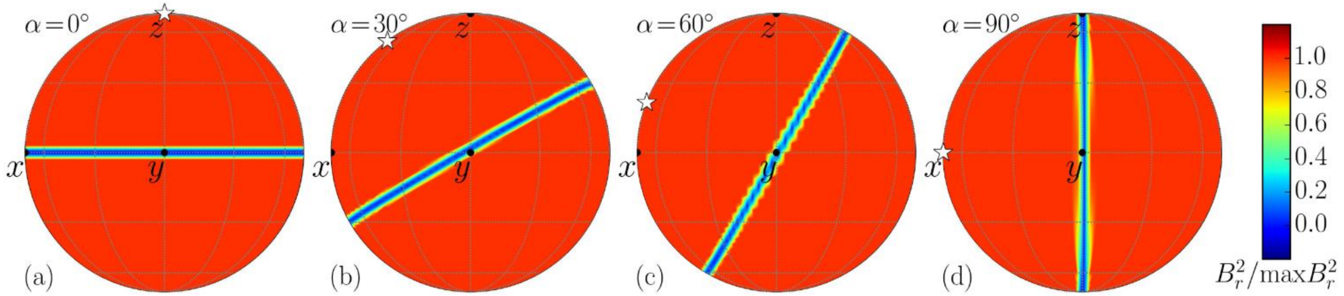
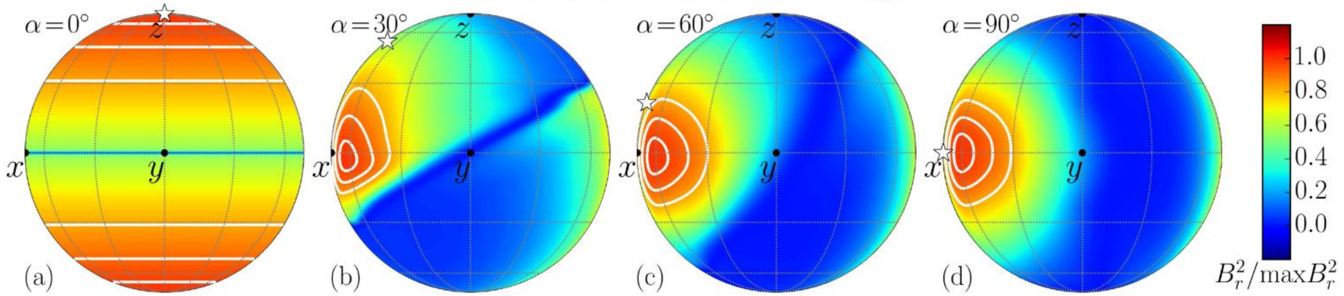


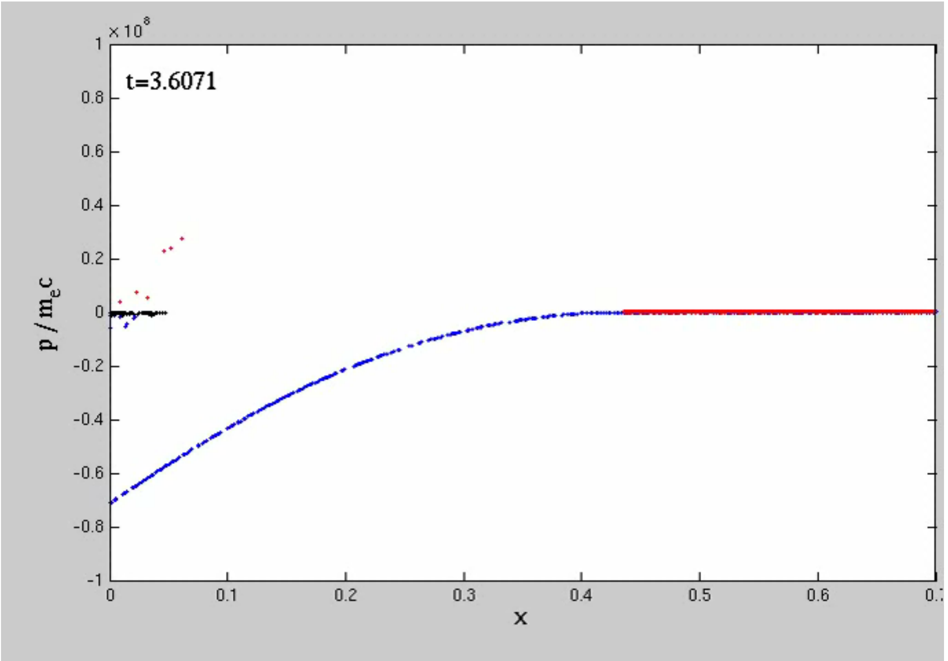
Figure 12. Colour-coded surface distribution of B_r^2 in the split-monopole solution (Bogovalov 1999). The current sheet, in which the radial magnetic field vanishes, describes the orientation of the current sheet in the numerical force-free solutions shown in Fig. 6.

Numerical force-free solution at $r = 6R_{\rm LC}$:



A.Tchekhovskoy, A.Philippov, A.Spitkovsky MNRAS, **457**, 3384 (2015)

Back to RS



A.Timokhin, MNRAS, **408**, 2092 (2010), A.Timokhin & J.Arons, MNRAS, **429**, 20 (2013)

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

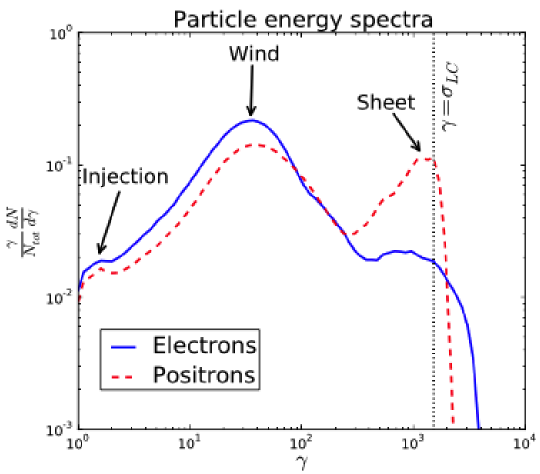
- Sparking if there is not enough plasma

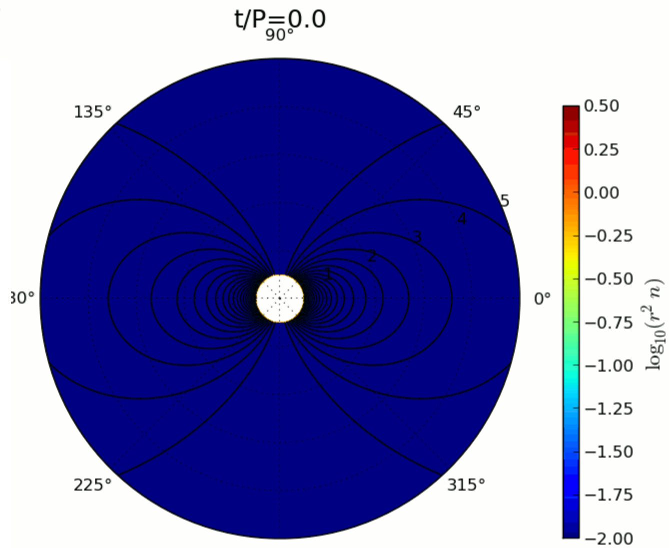
Modern time (2012 – …)

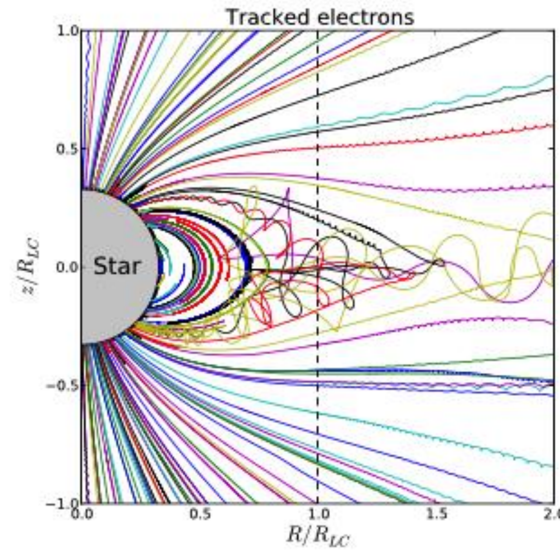
- PIC axysimmetric
- PIC inclined
- PIC reconnection

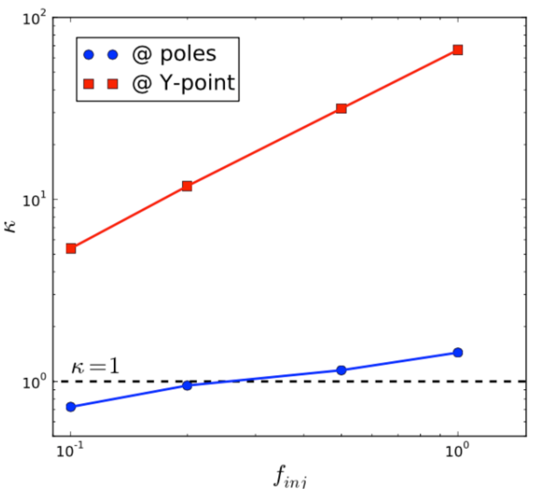
Particle in cell (PIC)

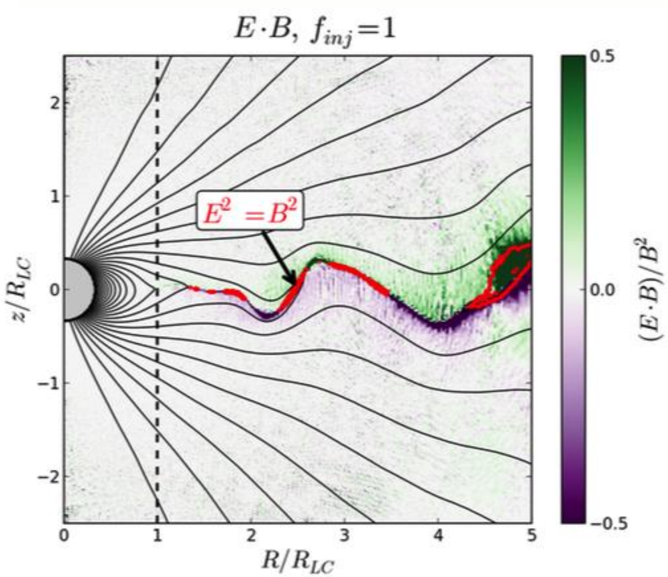
Cerutti B., A.Philippov, Parfrey K., Spitkovsky A.
MNRAS, **448**, 606 (2015)

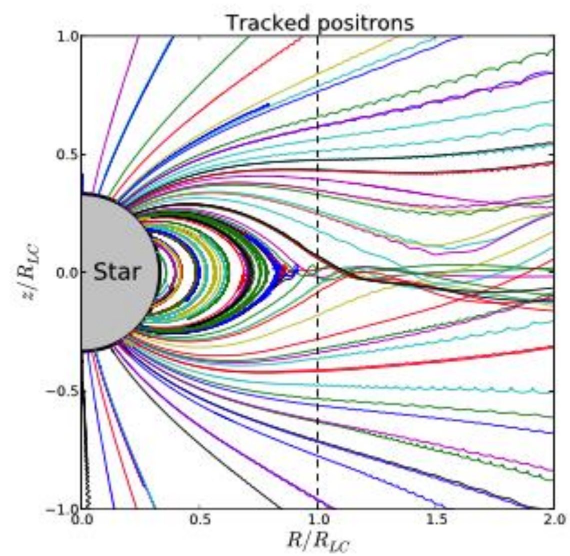




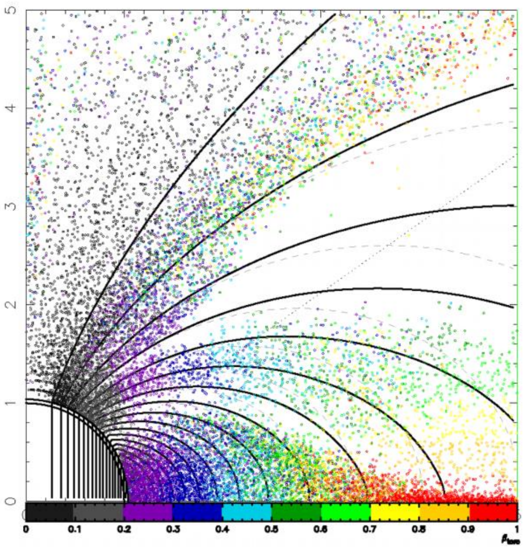


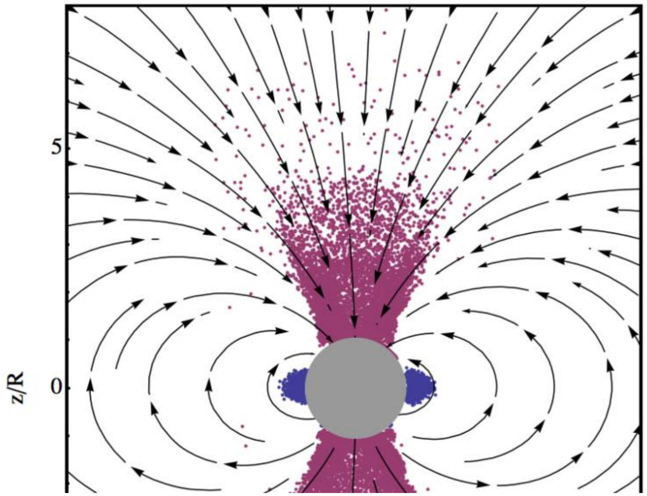


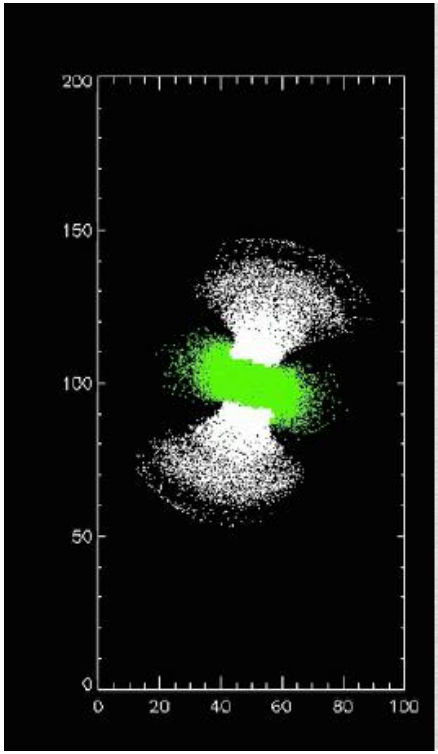




Dome







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

A.Philippov, A.Spitkosky
ApJ, **785**, L33 (2014)

Modern time (2012 – …)

Main results

- Particle acceleration up to $\Gamma \sim \sigma_M$ outide 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)

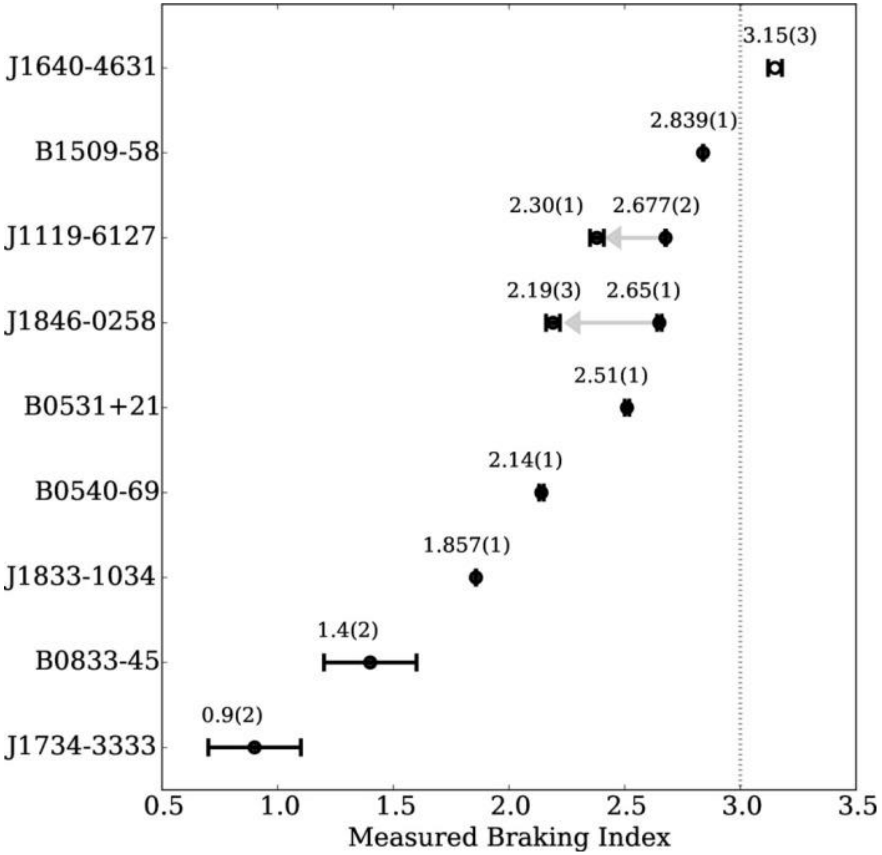
$$n_{\rm br} = \frac{\ddot{\Omega}\Omega}{\dot{\Omega}^2}$$

$$n_{\rm br}^{\rm VAC} = 3 + 2\tan^{-2}\chi \geqslant 3$$

$$n_{\rm br}^{\rm MHD} = 3 + 2\frac{\sin^2\chi\cos^2\chi}{(1+\sin^2\chi)^2}$$

$$3 \leqslant n_{\rm br}^{\rm MHD} \leqslant 3.25$$

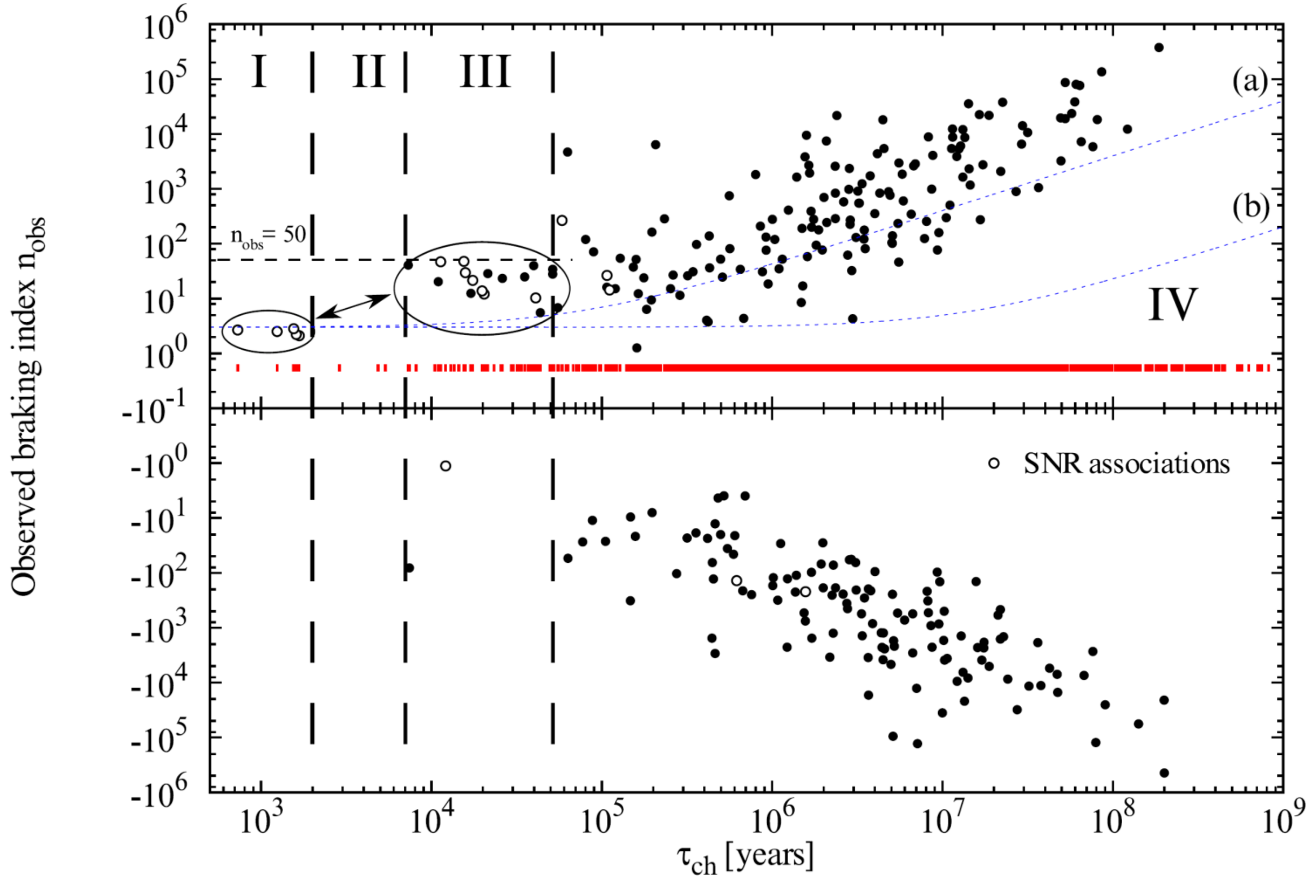
$$n_{\rm br} = 1{,}93 + 1{,}5\tan^2\chi$$



R.F.Archibald et al, ApJ, **819**, L16 (2016)

No pure experiment (braking index)

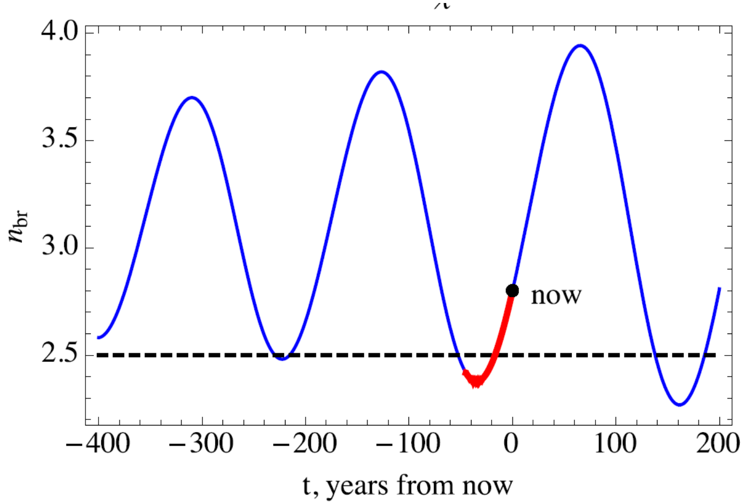
$$n_{\rm br} = \frac{\ddot{\Omega}\Omega}{\dot{\Omega}^2}$$



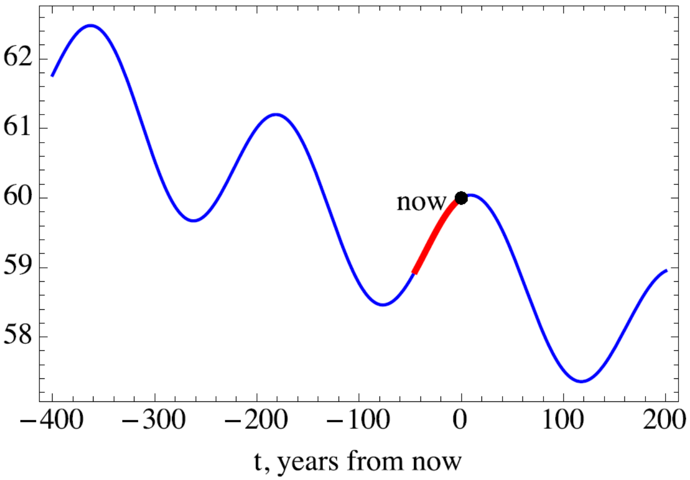
A.Biryukov, G.Beskin, S. Karpov, MNRAS, **420**, 103 (2012)

No pure experiment (braking index)

$$n_{\rm br} = \frac{\ddot{\Omega}\Omega}{\dot{\Omega}^2}$$



χ



L.Arzamasskiy, A.Philippov, A.Tchekhovsky, MNRAS, **453**, 3540 (2015)

Current losses

$$I_r\dot{\Omega} = K_{||}^A + [K_{\perp}^A - K_{||}^A]\sin^2\chi,$$
$$I_r\Omega\dot{\chi} = [K_{\perp}^A - K_{||}^A]\sin\chi\cos\chi.$$

- One-to-one correspondence

  χ evolves to 90 deg. if $W_{tot}(0) > W_{tot}(90)$, $n_{br} < 3$

  χ evolves to 0 deg. if $W_{tot}(0) < W_{tot}(90)$, $n_{br} > 3$
- For BGI $i_A \sim 1$
- For Michel-Bogovalov $\left[K_{\perp}^{(A)} - K_{||}^{(A)}\right] = 0$
- 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…