

P.N.Lebedev Physical Institute



# Radio pulsars

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# Radio pulsars in seven statements

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## Everything is known

Radio pulsars are rotating solitary\* neutron stars

Mass
Radius
Rotating period
Magnetic field
Radio luminosity
Flux
Coherent mechanism

 $M \sim 1.4 \ M_{\odot}$   $R \sim 10 \ \text{km}$   $P \sim 1 \ \text{s}$   $B_0 \sim 10^{12} \ \text{G}$   $L_r \sim 10^{28} \ \text{erg/s}$   $S_{1400} \sim 10 \ \text{mJy}$  $T_b \sim 10^{28} \ \text{K}$ 



#### \* no accretion from the companion

### Jocelyn Bell, <u>Antony Hewish</u>, 1967





#### **First observations**





#### PPdot – diagram



#### Mean pulse



#### **Dispersion measure DM**





Double

T.Hankins, J.Rankin, AJ, **139**, 168 (2010)



Single

T.Hankins, J.Rankin, AJ, **139**, 168 (2010)



Spectrum

#### A.V.Bilous et al (LOFAR team), A&A, 591, A134 (2016)



#### Frequency standard PSR B1937+21

C.Vilal, https://ui.adsabs.harvard.edu/abs/2017arXiv170403316V/abstract





St Catherine's Church, Gdańsk http://www.atnf.csiro.au/research/pulsar/psrcat



## Everything is known

Radio pulsars are rotating solitary\* neutron stars

- Mass
- •Radius
- Rotating period
- Magnetic field
- Radio luminosity
- •Flux

•Coherent mechanism  $T_{\rm b} \sim 10^{28} (10^{40}) \, {\rm K}$ 

$$\begin{split} M &\sim (1.4 - 2.0) \, M_\odot \\ R &\sim (12 - 14) \, \mathrm{km} \\ P &\sim (0.00139 - 4.8) \ (23) \, \mathrm{s} \\ B_0 &\sim (10^8 - 10^{13}) \ (10^{15}) \, \mathrm{G} \\ L_r &\sim (10^{26} - 10^{29}) \, \mathrm{erg/s} \\ S_{1400} &\sim (1 - 1000) \, \mathrm{mJy} \\ T_\mathrm{b} &\sim 10^{28} \ (10^{40}) \, \mathrm{K} \end{split}$$

#### \* no accretion from the companion

## Nothing is known

No real communication between theoreticians and observers

1968 – 1983 Hellas, Rome (both magnetosphere and radiation)
1983 – 1999 Dark ages (actually no study at all)
1999 – p.t. Renaissance (but magnetosphere only)

<u>We do not know up to now</u>Evolution of inclination angleMechanism of coherent radio emission

### Some delusions

<u>Magneto-dipole losses exist</u> (they are absent)

Magnetic field sweepback (it is much larger)

**Classification of modes** 

- O-mode cannot escape (it can)
- V and p.a. signs determination
- 'Hollow cone' model

Propagation effects play no role (they play) Refraction is not important (it is important) Cyclotron absorption is negligible (forms mean profile) RVM + A/R (not only! Limiting polarization)

### Statement #1

### The paradigme

Two key ideas:•radio pulsars are electromagnetic devices•radio pulsars are quantum devices

## Key electromagnetic idea

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

Magneto-dipole (vacuum) losses

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



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

In reality, it isn't true (magnetosphere is filled with plasma), but it's enough for evaluation.

### Key electromagnetic idea

The Moment of Truth – Pulsar in the Crab Nebula P = 0.033 s, $dP/dt = 4 \ 10^{-13}$ 



Total energy losses  $W_{tot} = -J_r \Omega d\Omega/dt \sim 5 \ 10^{38} \text{ erg/s}$ Dynamical age  $\tau = P/(2 \ dP/dt) \sim 1000 \text{ years}$  (AD1054) Optical emission



### Key quantum idea

#### Electron-positron pair creation P.A.Sturrock, ApJ, **164**, 529 (1971)









M.Ruderman & P.Sutherland (1975) V.Ya.Eidman group (1975) J.Arons et al (1977-1981) L.Mestel et al

## Energy losses

Vacuum magneto-dipole (alignment) F.Pacini, Ap Lett., **3**, 225 (1968) + ...

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

**BGI** (counter-alignment)

VB, A.V.Gurevich, Ya.N.Istomin, Sov. Phys. JETP, 85, 401 (1983)

$$W_{\rm tot}^{\rm (BGI)} = i_{\rm s}^{\rm A}(\Omega, B) \frac{f_*^2(\chi)}{4} \frac{B_0^2 \Omega^4 R^6}{c^3} \cos^2 \chi$$

MHD (alignment)

A.Spitkovsky, ApJ, 648, L51 (2006) + ...

$$W_{\rm tot}^{\rm (MHD)} \approx \frac{1}{4} \, \frac{B_0^2 \Omega^4 R^6}{c^3} \, (1 + \sin^2 \chi)$$

## Energy losses

Vacuum magneto-dipole (alignment) F.Pacini. Ap Lett., 3, 225 (1968) + ...  $W_{\text{tot}}^{(\text{V})} = -I_{\text{r}}\Omega\dot{\Omega} = \frac{1}{6} \frac{B_0^2 \Omega^4 R^6}{c^3} \sin^2 \chi$ 

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### Statement #2

Magnetosphere is filled with e<sup>-</sup>-e<sup>+</sup> plasma Plasma screens magneto-dipole radiation

## ID

right ascension declination

- Name PSR B\*\*\*\*+\*\* (1950), J\*\*\*\*+\*\*\*\* (2000)
- Period P
- Period derivative dP/dt
- Second derivative  $d^2P/dt^2$
- Mean profile (pulse width W)
- Dispersion measure

• Radio flux  $S_{1400}$ 

$$DM = \int_{0}^{L} n_{e} dl = \overline{n}_{e} L$$
$$RM = 0$$

### Determining P ( Pdot, etc.), do not forget about

- Proper motion
- Glitches
- Precession (?)
- Subpulse drifting
- Mode switching
- Nullings
- RRATS
- FRB
- Binary systems
- GR effects

#### **Proper motion**

G.Hobbs, D.R.Lorimer, A.G.Lyne, M.Kramer, MNRAS, 360, 974 (2005)



~ 400 PSRs, 100 - 1000 km/s, 10 - 100 mas/yr

#### **Glitches**

571 × 559

#### C.M.Espinoza, A.G.Lyne, B.W.Stappers, M.Kramer, MNRAS, 414, 1679 (2011)



#### Braking index

#### R.F.Archibald et al, ApJ, **819**, L16 (2016) $\Omega\Omega$ $n_{\rm br} = \frac{1}{\dot{\Omega}^2}$ J1640-4631 B1509-58 $n_{\rm br}^{\rm VAC} = 3 + 2 \tan^{-2} \alpha \ge 3$ J1119-6127 $n_{\rm br}^{\rm MHD} = 3 + 2 \frac{\sin^2 \alpha \cos^2 \alpha}{(1 + \sin^2 \alpha)^2}$ J1846-0258 B0531+21 B0540-69 $3 \leq n_{\rm br}^{\rm MHD} \leq 3.25$ J1833-1034 B0833-45 $n_{\rm br}^{\rm BGI} = 1,93 + 1,5 \tan^2 \chi$



~ 300 PSRs,

### **Braking index**

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



~ 300 PSRs,

### Braking index

~ 300 PSRs,

 $n_{\rm br}$ 

 $\ddot{\Omega}\Omega$ 

 $\dot{\Omega}^2$ 

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

**Precession for** 

•Crab pulsar (
$$n_{\rm br} = 2.5$$
)

•MHD model (  $3 \leq n_{\rm br}^{\rm MHD}$ 





≤ 3.25

#### Subpulse drifting

P.Weltevrede, B.W.Stappers, R.T.Edwards, A&A, 469, 607 (2007).



~ 100 PSRs,

### Timing B0945+10

#### Mode switching

W.Hermsen, J.W.T.Hessels, T.Kuiper et al, Science, **339**, 436 (2013)



#### Nulling

#### V.Gajjar, B.C.Joshi, M.Kramer, MNRAS, 424, 1197 (2012)



~ 100 PSRs,

#### **Nulling**

VB, E.E.Nokhrina, ApSS 308, 569 (2007), A.V.Gurevich, Ya.N.Istomin (2007)

#### Half-time job pulsars



### Timing <u>RRATS</u> (Rotating RAdio TransientS)

~ 20 PSRs,

A.G.Lyne. Proc. Sci., Proc. "Bursts, Pulses and Flickering" (2007)



### Timing <u>RRATS (Rotating RAdio TransientS)</u>

A.G.Lyne. Proc. Sci., Proc. "Bursts, Pulses and Flickering" (2007)



~ 20 PSRs,
#### **Timing** <u>FRB</u> (http://www.frbcat.org/)

D.Thornton, B.Stappers, M.Bailes et al, Science, 341, 53 (2013)



~ 80 PSRs, (?)

#### Timing Radio pulsars in binary systems

A.M.Archibald, I.H.Stairs, S.M.Ransom et al, Science, 324, 1411 (2009)



~ 300 PSRs, Pb ~ 1 – 10 d (3 yr), WD

#### Timing Radio pulsars in binary systems

A.M.Archibald, I.H.Stairs, S.M.Ransom et al, Science, 324, 1411 (2009)



~ 300 PSRs, Pb ~ 1 – 10 d (3 yr), WD

#### Timing <u>GR effects</u> – post-Newtonian corrections

Orbit precession

$$\dot{\omega} = 3\left(\frac{P_{\rm b}}{2\pi}\right)^{-5/3} \left(\frac{G}{c^3}\right)^{2/3} (M_1 + M_2)^{2/3} (1 - e^2)^{-1}$$



$$\Delta P = P\left[\left(\frac{K_1}{c}\cos\omega + \frac{eA}{c^2}\right)(\cos E + e) - \frac{K_1}{c}\sin\omega\sin E\right]$$
$$\gamma_{\rm p} = e\left(\frac{P_{\rm b}}{2\pi}\right)^{1/3} \frac{G^{2/3}}{c^2} \frac{M_2(M_1 + 2M_2)}{(M_1 + M_2)^{4/3}}$$

 $\Delta t_{\rm S} = -2r_{\rm S} \ln \left[1 - e \cos E - s \left[\sin \omega (\cos E - e) + (1 - e^2)^{1/2} \cos \omega \sin E\right]\right]$ 

~ 10 PSRs, Pb ~ 2 – 7 hr, NS

# <u>GR effects</u> – gravity waves

J.Taylor, J.Weisberg, ApJ, 253, 908 (1982)

#### B1913+16



~ 10 PSRs, Pb ~ 2 – 7 hr, NS



#### Timing <u>GR effects</u> – gravity waves

#### B1913+16 <u>R. Hulse</u>





$$\frac{\dot{P}_{\rm b}^{\rm (obs)}}{\dot{P}_{\rm b}^{\rm (th)}} = 1,0013 \pm 0,0021$$

~ 10 PSRs, Pb ~ 2 – 7 hr, NS











# Timing

#### **GR effects**

#### J.Weisberg, Y.Huang, ApJ, 829, 55 (2016)

#### Table 3

Comparison of Gravitational Radiation-Induced Orbital Decay with GR Prediction in Binary Pulsars

PSR	$\dot{P}_{\mathrm{b}}^{\mathrm{intr}}/\dot{P}_{\mathrm{b}}^{\mathrm{GR}}$	Ref.
$\begin{array}{c} J0348{+}0432\\ J0737{-}3039\\ J1141{-}6545\\ B1534{+}12\\ J1738{+}0333\\ J1756{-}2251\\ J1906{+}0746\\ B1913{+}16\\ B2127{+}11C \end{array}$	$\begin{array}{c} 1.05 \pm 0.18 \\ 1.003 \pm 0.014 \\ 1.04 \pm 0.06 \\ 0.91 \pm 0.06 \\ 0.94 \pm 0.13 \\ 1.08 \pm 0.03 \\ 1.01 \pm 0.05^{\mathrm{a}} \\ 0.9983 \pm 0.0016 \\ 1.00 \pm 0.03 \end{array}$	Antoniadis et al. (2013) Kramer et al. (2006) Bhat, Bailes, & Verbiest (2008) Stairs et al. (2002) Freire et al. (2012) Ferdman et al. (2014) van Leeuwen et al. (2015) This work Jacoby et al. (2006)



0.35

Time (s)

0.40

0.30 0.35 0.40 0.45 0.30 Time (s)

~ 1 PSRs, Pb ~ 0.0001 s, NS

### Statement #3

- Even timing is a very exciting business
- •Asymmetric Shapiro delay (yes!)
- •Post-post-Newtonian correction
- Cosmological gravity waves

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

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

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

$$I^{(\rm MHD)} = \frac{P\sin\chi}{\cos^2\chi}$$

= alignment



#### Renaissance (1999 – p.t.)

I.Contopoulos, D.Kazanas & Ch.Fendt, S.Bogovalov, A.Grusinov, D.Uzdensky, L.Mestel et al, J.Ogura & Y.Kojima, A.Harding & A.Muslimov, A.Spitkovsky, A.Timokhin, S.Komissarov, R.Lovelace, L.Turner & M.Romanova, J.McKinney, J.Arons et al, A.Gurevich & Ya.Istomin, VB & E.Nokhrina, A.Chen & A.Beloborodov, J.Petri,C.Kalapotharakos, A.Philippov, A.Tchekhovskoy & J.Li, .S.Yuki & S.Shibata, M.Belyaev, B.Cerutti, L.Arzamasskiy, VB, Kh.Pirov, M.Rashkovetskyi, A.Galishnikova & E.Novoselov, K.Parfrey, S.Gralla

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Russian-speaking – 50%

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Russian-speaking – 50% In Russia – 30% (15% from all)

# Particle in cell (PIC)





#### Pair creation



J. K. Daugherty, A. K.Harding, ApJ, **252**, 337 (1982)

Free pass

 $l_{\gamma} = \frac{8}{3\Lambda} R_{\rm c} \frac{B_{\bar{h}}}{B} \frac{m_{\rm e} c^2}{\mathscr{E}_{\rm ph}}$ 

 $\gamma \approx \frac{1}{\theta} \approx \frac{R_{\rm c}}{l_{\gamma}}$ 



#### Pair creation



A.Timokhin, MNRAS, **368**, 1055 (2006)

$$H_{\rm RS} = 1.1 \times 10^4 |\cos \theta_b|^{-3/7} R_{\rm c,7}^{2/7} P^{3/7} B_{12}^{-4/7} {\rm cm}$$

### Pair creation



A.Timokhin, MNRAS, **368**, 1055 (2006)

$$H_{\rm RS} = 1.1 \times 10^4 |\cos \theta_b|^{-3/7} R_{\rm c,7}^{2/7} P^{3/7} B_{12}^{-4/7} {\rm cm}$$

# Theory of Radio Emission

Properties of the outgoing plasma

(consensus)

Number density of the electron-positron plasma

$$n = \lambda n_{\rm GJ}$$

(primary beam  $n \sim n_{\rm GJ}$ )

**Multiplicity parameter** 

 $\lambda \sim 10^4$ 

Particle energy: beam  $-\gamma \sim 10^7$ , main flow  $\gamma \sim 100$ Ejection rate  $10^{32}$  pairs/s (Crab  $-10^{40}$  pairs/s)

PPdot – diagram



PPdot – diagram



#### MAGNETIC POLES AND THE POLARIZATION STRUCTURE OF PULSAR RADIATION

The very beginning:

V. RADHAKRISHNAN AND D. J. COOKE Radiophysics Laboratory, CSIRO, Sydney, Australia

V.Radhakrishnan, D.J.Cooke, Ap Lett., 3, 225 (1969)





#### P.Weltevrede, S.Johnston, MNRAS, 391, 1210 (2008)



#### Orthogonal modes

D.Stinebring, J.Cordes, J.Rankin, J.Weisberg, V.Boriakoff, ApJS, 55, 279 (1984)



FIG. 5.—PSR 0950+08: Polarization distribution display

# The signs!!!

J.E.Everett, J.Weisberg. ApJ, 553, 341 (2001)

Furthermore, as pointed out by Damour & Taylor (1992) and Arzoumanian et al. (1996), Eq. 1, used by essentially all researchers who have fit the RVM model to data, was derived with the convention that the polarization position angle,  $\psi'$ , increases *clockwise* on the sky. This is contrary to the usual astronomical convention that *measured* polarization position angle  $\psi$  increases *counterclockwise* on the sky.

$$p.a. = \arctan\left(\frac{\sin\alpha\sin\phi}{\sin\alpha\cos\zeta\cos\phi - \sin\zeta\cos\alpha}\right)$$

$$\tan(\psi' - \psi'_0) = \frac{\sin\alpha\sin(\phi - \phi_0)}{\sin\zeta\cos\alpha - \cos\zeta\sin\alpha\cos(\phi - \phi_0)}$$

$$\chi = \tan^{-1} \left( \frac{\sin \alpha \sin(\varphi - \varphi_{\circ})}{\sin \xi \cos \alpha + \cos \xi \sin \alpha \cos(\varphi - \varphi_{\circ})} \right) + \chi_{\circ}$$

# The signs!!!

#### J.E.Everett, J.Weisberg, ApJ, 553, 341 (2001)

DICTIONARY AND CONVERSION TABLE FROM EARLIER WORK FOR GEOMETRICAL BEAM PARAMETERS. (SEE EQS AND ENSUING DISCUSSION.)

Investigators	$\psi$	Colatitude of Observable Magnetic Pole, $\alpha$		Impact Parameter of Line of Sight	
and	Convention	w.r.t. $(+\vec{\Omega})$ Spin Axis		w.r.t. Observable Magnetic Pole	
Method	Problem?	Confined	Relation to	Symbol in	Relation to
		to First	our $\alpha$	Original	$\mathrm{our}\;eta$
		Quadrant?	$(\alpha_{original} \to \text{our } \alpha)$	Paper	$(Symbol_{original} \to \text{our } \beta)$
Current Work (RVM)	no	no	$\alpha  ightarrow \alpha$	eta	eta ightarroweta
NV82 (RVM)	no	yes	If $(d\psi/d\phi \text{ and } \beta_{NV})$ both have same sign, then $\pi - \alpha_{NV} \to \alpha$ . Otherwise, $\alpha_{NV} \to \alpha$ .	$\beta_{NV}$	If $d\psi/d\phi > 0$ , then $- \beta_{NV}  \rightarrow \beta$ . If $d\psi/d\phi < 0$ , then $ \beta_{NV}  \rightarrow \beta$ .
LM88 $(E/G)$	n/a	yes	As the sign of $\beta_{LM}$ was not published, either $\alpha_{LM} \rightarrow \alpha$ or $\pi - \alpha_{LM} \rightarrow \alpha$ are possible. We selected one based on con- sistency with our fits.	$egin{aligned} & eta_{LM} \ ( ext{magnitude only} \  ext{was published}) \end{aligned}$	If $d\psi/d\phi > 0$ , then $- \beta_{LM}  \to \beta$ . If $d\psi/d\phi < 0$ , then $ \beta_{LM}  \to \beta$ .
$\begin{array}{c} \mathrm{BCW91}\\ \mathrm{(RVM)} \end{array}$	yes	no	$\pi - \alpha_{BCW} \to \alpha.$	$\sigma_{BCW}$	$\sigma_{BCW} \to -\beta$
m R90,93a,b (E/G)	n/a	yes	If $(d\psi/d\phi \text{ and } \beta_R)$ both have same sign, then $\pi - \alpha_R \to \alpha$ . Otherwise, $\alpha_R \to \alpha$ .	$\beta_R$	If $d\psi/d\phi > 0$ , then $- \beta_R  \to \beta$ . If $d\psi/d\phi < 0$ , then $ \beta_R  \to \beta$ .
$\begin{array}{c} \mathrm{HX97a,b}\\ \mathrm{(RVM)} \end{array}$	yes	no	$\pi -  \alpha_{HX}  \to \alpha.$	$\sigma_{HX}$	If $\alpha_{HX} > 0$ , then $\sigma_{HX} \to -\beta$ . Otherwise, $\sigma_{HX} \to \beta$ . <sup><i>a</i></sup>

Sign of	Sign of	Sign of Impact Param.	Colatitude of	Line of Sight Trajectory
$Slope^{a}$	$Slope^{b}$	of Line of Sight w.r.t.	Observable Mag-	w.r.t.
$\frac{d\psi}{d\phi} _{max}$	$rac{d\psi'}{d\phi} _{max}$	Obs. Mag. Pole, $\beta$	netic Pole, $\alpha$	Observable Magnetic Pole
			$<\pi/2$	Outer (Equatorward) <sup><math>c</math></sup>
Negative	Positive	Positive		
			$> \pi/2$	Inner (Nearest $[-\vec{\Omega}]$ Spin Poleward)
			$<\pi/2$	Inner (Nearest $[+\vec{\Omega}]$ Spin Poleward)
Positive	Negative	Negative		
			$>\pi/2$	Outer (Equatorward) <sup><math>c</math></sup>

#### PULSAR GEOMETRIES. III. THE HOLLOW-CONE MODEL

LUDWIG OSTER

Joint Institute for Laboratory Astrophysics, University of Colorado, and National Bureau of Standards; and Department of Physics and Astrophysics, University of Colorado, Boulder

AND

L.Oster, W.Sieber, ApJ, 210, 220 (1976)

The very beginning:

WOLFGANG SIEBER Max-Planck-Institut für Radioastronomie, Bonn





#### TOWARD AN EMPIRICAL THEORY OF PULSAR EMISSION. I. MORPHOLOGICAL TAXONOMY

The very beginning: J.Rankin, ApJ, **274**, 333 (1983)

JOANNA M. RANKIN Department of Physics, University of Vermont







#### Model explains:

**Morfology** 

Periphery passage
– single profiles, small change of the *p.a.*Central passage
– double profiles, *p.a.* changes up to 180°





#### Model explains:



100

J.Rankin, ApJ, 274, 333 (1983)

Model explains:

 $\frac{\text{Mean profile width}}{W_{50} = \frac{3}{2} \left( f_* \frac{\Omega R}{c} \right)^{1/2} \left( \frac{r_{\text{rad}}}{R} \right)^{1/2}}$  $W_{50} = \frac{W_0}{\sqrt{P}}$  $W_r^{\text{obs}} = \frac{W_0}{\sin \chi}$ 


### "Hollow cone" model

#### Model explains:

#### Subpulse drift







M.Ruderman, P.Sutherland, ApJ, **196**, 51 (1975) Ruderman, J.Gil, A&A, **460**, L31 (2006)



longitude (°)

# Everything is clear

- Stability of pulsation neutron star rotation
- Energy source kinetic energy of rotation
- Mechanism of energy loss electrodynamics
- Neutron star is a radio pulsar if there is secondary electron-positron generation near magnetic poles

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- Stability of pulsation neutron star rotation
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- Neutron star is a radio pulsar if there is secondary electron-positron generation near magnetic poles

Radio emission – ????

# Theory of the Radio Emission

- Properties of the outgoing plasma (consensus)
- Coherent mechanism

   Base instability
   Saturation (nonlinear effects)

   (no common point of view)
   Propagation effects
- (there was the missing link)

# Theory of the Radio Emission

 Properties of the outgoing plasma (consensus)
 Number density of the electron-positron plasma

$$n = \lambda n_{\rm GJ}$$

(primary beam  $n \sim n_{\rm GJ}$ )

**Multiplicity parameter** 

 $\lambda \sim 10^4$ 

Particle energy: beam –  $\gamma \sim 10^7$ , main flow  $\gamma \sim 100$ Ejection rate 10<sup>32</sup> pairs/s (Crab – 10<sup>40</sup> pairs/s)

#### Aberration/Retardation

#### A RELATIVISTIC MODEL OF PULSAR POLARIZATION

M. BLASKIEWICZ<sup>1</sup>

Department of Physics and National Astronomy and Ionosphere Center, Cornell University

J. M. CORDES<sup>1</sup>

Astronomy Department and National Astronomy and Ionosphere Center, Cornell University

AND

I. WASSERMAN<sup>1</sup> Astronomy Department, Cornell University

M.Blaskiewicz, J.Cordes, I.Wasserman, ApJ, 370, 643 (1991)



corotation component of the plasma velocity is included. The model predicts that the centroid of the position angle curve arrives later than the centroid of the intensity profile by an amount 4r/c, where r is the emission radius. Our assumptions should hold for coherent curvature emission and for plasma maser emission mecha-

#### Aberration/Retardation

Shift to the right

S.C.Rookyard, P.Weltevrede, S.Johnston, MNRAS, 446, 3367 (2015)



## 'Hollow cone' – implicit assumptions

- Rectilinear propagation of radio waves
- Cyclotron absorption is not important
- Polarization is formed in the region of radiation

# 'Hollow cone' – implicit assumptions

- Rectilinear propagation of radio waves
- Cyclotron absorption is not important
- Polarization is formed in the region of radiation

All these points are incorrect



#### Refraction

#### J.Arons, J.Barnard. ApJ, **302**, 120 (1986) + ...

WAVE PROPAGATION IN PULSAR MAGNETOSPHERES



#### Four, not three waves!

VB, A.V.Gurevich, Ya.N.Istomin. ApSS, 146, 205 (1988)



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#### Four, not three waves!

VB, A.V.Gurevich, Ya.N.Istomin. ApSS, 146, 205 (1988)



## Propagation



# Core & Conal VB, A.V.Gurevich, Ya.N.Istomin. ApSS, **146**, 205 (1988) $r_{\rm A} \approx 10^2 R \,\lambda_4^{1/3} \,\gamma_{100}^{1/3} \,B_{12}^{1/3} \,\nu_{\rm CHz}^{-2/3} \,P^{-1/3}$ Core – extraordinary Conal – ordinary iode magnetic axis O-mode low frequency A.Noutsos et al. (LOFAR), A&A, 576, 26 (2015)



# Statements #4, 5

- O-mode can escape
- Refraction is important

#### Observations

VB, A.V.Gurevich, Ya.N.Istomin, ApSS, 146, 205 (1988)

$$\begin{split} W_{\mathbf{X}}^{(1)} &\approx 3.6^{\circ} \left(\frac{P}{1\,s}\right)^{-3/4} \left(\frac{\nu}{1\,\mathrm{GHz}}\right)^{-1/2} \left(\frac{\lambda}{10^4}\right)^{1/8} \left(\frac{B}{10^{12}\mathrm{G}}\right)^{1/8} \left(\frac{\gamma}{100}\right)^{7/8}, \\ W_{\mathbf{0}}^{(2)} &\approx 7.8^{\circ} \left(\frac{P}{1\,s}\right)^{-0.43} \left(\frac{\nu}{1\,\mathrm{GHz}}\right)^{-0.14} \left(\frac{\lambda}{10^4}\right)^{0.07} \left(\frac{B}{10^{12}\mathrm{G}}\right)^{0.07} \left(\frac{\gamma}{100}\right)^{-0.11}, \\ W^{(2)} &\approx 10^{\circ} \left(\frac{P}{1\,s}\right)^{-0.5} \left(\frac{\nu}{1\,\mathrm{GHz}}\right)^{-0.29} \left(\frac{\lambda}{10^4}\right)^{0.1} \left(\frac{B}{10^{12}\mathrm{G}}\right)^{0.1} \left(\frac{\gamma}{100}\right)^{-0.05}. \end{split}$$

 $W \sim v^{-\beta} (1988)$ 

#### VB, A.V.Gurevich, Ya.N.Istomin. Ap&SS, **146**, 205 (1988)



Fig. 7.24. Pulsar distribution over the quantity  $\bar{\beta}$  (Rankin, 1983b). Arrows indicate the expected values (7.152)–(7.154).

 $W \sim v^{\delta}$  (2002)

B0301+19 430 MHz

B0525+21 430 MHz

pu

ower

A A

D.Mitra, J.Rankin. ApJ. 577, 322 (2002)

Half-power W	idths — Gro	oup A <b>(O-</b>		non- no- no- no- no- no- no- no- no- no-
0301 + 19	1.040	$1.8 \pm 0.5 \times 10^3$	$-0.185 \pm 0.03$	
0525 + 21	0.633	$262\pm100$	$-0.15 \pm 0.01$	Position Angle [
1237 + 25	1.042	$9.6\pm5.0\times10^3$	$-0.15 \pm 0.02$	-30 -20 -10 0 10 2
2045 - 16	0.875	$5.0\pm3.0\times10^3$	$-0.14 \pm 0.02$	

10% Widths –	– Group A		
0301 + 19	1.040	$2.6\pm0.4\times10^5$	$-0.13 \pm 0.02$
0525 + 21	0.633	$2.9\pm1.2\times10^3$	$-0.13 \pm 0.02$
1237 + 25	1.042	$1.6\pm1.5 imes10^3$	$-0.13 \pm 0.02$
2045 - 16	0.875	$1.0\pm1.0 imes10^5$	$-0.12 \pm 0.03$

# LOFAR W ~ $\nu^{\delta}$ (2015)

M.Pilia et al, A&A, **586**, 34 (2016)



B0943+10, X-mode! A.Bilous et al, A&A, **572**, 52 (2014)



 $w_{\rm extrap}(v) = 0.384v^{-0.567}$ 

# LOFAR W ~ $\nu^{\delta}$ (2015)

M.Pilia et al, A&A, **586**, 34 (2016)



B0943+10, X-mode! *A.Bilous* et al, A&A, **572**, 52 (2014)



 $w_{\rm extrap}(v) = 0.384v^{-0.567}$ 

# LOFAR W ~ $\nu^{\delta}$ (2015)

M.Pilia et al, A&A, **586**, 34 (2016)



#### B0943+10, X-mode! *A.Bilous* et al, A&A, **572**, 52 (2014)



 $w_{\rm extrap}(v) = 0.384v^{-0.567}$ 

# Cyclotron absorption

A.B.Mikhailovsky, O.G.Onishchenko, G.I.Suramlishvili, S.E.Sharapov. Sov. Astron. Lett., **8**, 685 (1982)

$$\varepsilon \approx 1 + \frac{\omega_p^2}{\omega^2} < \frac{\varpi}{(\omega_B - \gamma \varpi)} >$$

$$\operatorname{Im} k \approx -i\pi \, \frac{\omega_p^2}{2\omega c} < \varpi \delta(\omega_B - \gamma \varpi) >$$

$$\tau \approx \lambda (1 - \cos \theta_{\rm res}) \frac{r_{\rm res}}{R_{\rm L}}$$

$$\tau \approx \frac{4\pi^2 e^2}{m_{\rm e} c} \int_0^\infty \int_0^\infty n_{\rm e}(l) \frac{\tilde{\omega}}{\omega} f(\gamma) \delta \left( |\omega_B| \sqrt{1 - \frac{U^2}{c^2}} - \gamma \tilde{\omega} \right) d\gamma dl$$
Optical depth
$$= \frac{4\pi^2 e^2}{mc} \int_0^\infty n(l) \frac{1}{\omega} f\left( \frac{|\omega_B| \sqrt{1 - U^2/c^2}}{\tilde{\omega}} \right) dl. \quad (60)$$

## Cyclotron absorption

A.B.Mikhailovsky, O.G.Onishchenko, G.I.Suramlishvili, S.E.Sharapov. Sov. Astron. Lett., **8**, 685 (1982)

$$r_{\rm res} \approx 1.8 \times 10^3 R \cdot v_{\rm GHz}^{-1/3} \gamma_{100}^{-1/3} B_{12}^{1/3}$$
  
 $\tau = \lambda (1 - \cos \theta_{\rm res}) \frac{r_{\rm res}}{R_{\rm L}}$ 

If  $\lambda \sim 10^4$ , then cyclotron absorption is too large...

#### Through the cyclotron resonance



S.Petrova. MNRAS, **366**, 1539 (2006)



# Cyclotron absorption



# Cyclotron absorption

VB, A.A.Philippov, MNRAS, 425, 814 (2012)

Ω



v = 0.03 GHz

15

10

15

# Statement #6

# Cyclotron absorption can form the mean profile

Escaping into vacuum, where  $\Delta n = 0$ , and, hence, the geometric optics approximation becomes invalid, the polarizations of normal modes do not follow the orientation of the magnetic field in the picture plane.

 $c/\omega\Delta n > r$ 



- Four equtions (four Stokes parameter)
- V.N.Sazonov. Sov. Phys. JETP, 29, 578 (1969)
- S.A.Petrova, Yu.E.Lyubarskii. Astron. Ap., 355, 1168 (2000)
- A.E.Broderick, R.D.Blandford. ApJ, **718**, 1085 (2010)
- Z.Wang, D.Lai, J.Han. MNRAS, **403**, 2 (2010)
- R.V.Shcherbakov, L.Huang. MNRAS, **410**, 1052 (2011)
- **Budden equation**
- V.V.Zheleznyakov. 1970, Radio Emission of the Sun and Planets, Pergamon, Oxford
- Kravtsov-Orlov approach
- Yu.A.Kravtsov, Yu.I.Orlov. 1990, Geometrical Optics
- of Inhomogeneous Media, Springer, Berlin

Location of the region where the polarization of the outgoing radiation is formed, e.g.,

A.F.Cheng, M.A.Ruderman. ApJ, **229**, 348, (1979) J.J.Barnard. Ap. J., **303**, 280 (1986) Z.Wang, D.Lai, J.Han. MNRAS, **403**, 2 (2000)

$$r_{\rm esc} \approx 10^3 R \,\lambda_4^{2/5} \,\gamma_{100}^{-6/5} \,B_{12}^{2/5} \,\nu_{\rm GHz}^{-2/5} \,P^{-1/5}$$

$$q \sim 10-100,$$
  
 $K \sim 1-10 \%$ 



 $lg(r/R_{\rm L})$
Main result

For ordinary wave (conal) the signs dp.a./dφ and V are to be opposite, and for the extraordinary wave (core) are to be the same.
This property depends neither on the sign Ωm, nor on the pole of the neutron star.

O-mode is to be wider (and mainly D) X-mode is to be narrower (and mainly S)



T.Hankins, J.Rankin, Astron. J., **139**, 168 (2010)



J.Han, R.Manchester, R.Xu, G.Qiao, MNRAS, 300, 373 (1998)

#### Core & Conal

Profile	$O_S$	O <sub>D</sub>	$X_S$	X <sub>D</sub>
Number	6	23	45	6
$\sqrt{P}W_{50}$	$6.8\pm$ $3.1$	$10.7{\pm}~4.5$	$6.5{\pm}~2.9$	$5.3\pm$ $3.0$

P.Weltevrede, S.Johnston. MNRAS, **391**, 1210 (2008) T.Hankins, J.Rankin. Astron. J., **139**, 168 (2010)

$$\begin{split} W^{(1)} &\approx 3.6^{\circ} \left(\frac{P}{1\,s}\right)^{-3/4} \left(\frac{\nu}{1\,\mathrm{GHz}}\right)^{-1/2} \left(\frac{\lambda}{10^4}\right)^{1/8} \left(\frac{B}{10^{12}\mathrm{G}}\right)^{1/8} \left(\frac{\gamma}{100}\right)^{7/8}, \\ W^{(2)} &\approx 7.8^{\circ} \left(\frac{P}{1\,s}\right)^{-0.43} \left(\frac{\nu}{1\,\mathrm{GHz}}\right)^{-0.14} \left(\frac{\lambda}{10^4}\right)^{0.07} \left(\frac{B}{10^{12}\mathrm{G}}\right)^{0.07} \left(\frac{\gamma}{100}\right)^{-0.11}, \\ W^{(2)} &\approx 10^{\circ} \left(\frac{P}{1\,s}\right)^{-0.5} \left(\frac{\nu}{1\,\mathrm{GHz}}\right)^{-0.29} \left(\frac{\lambda}{10^4}\right)^{0.1} \left(\frac{B}{10^{12}\mathrm{G}}\right)^{0.1} \left(\frac{\gamma}{100}\right)^{-0.05}. \end{split}$$

VB, Phys. Uspekhi, 61, 353 (2018)



**Figure 25.** Distribution of 170 O- and X-pulsars over  $W_r P^{1/2}$  (in degrees) taken from [222]. The distribution maxima exactly correspond to predictions (129)–(131).

Precessing pulsar J1906+0746 G.Desvignes, M.Kramer et al, Science (in press)





#### Precessing pulsar J1906+0746 G.Desvignes, M.Kramer et al, Science (in press)



Precessing pulsar J1906+0746 G.Desvignes, M.Kramer et al, Science (in press)



#### Statement #7

# Limiting polarization is the key process

#### Conclusion

Go ahead!

#### Conclusion

Go ahead!

And thanks for support.

#### Main parameters

 $\Delta n = -\frac{1}{2} < \frac{\omega_p^2 \omega_B^2}{\gamma^3 \varpi^2 (\omega_B^2 - \gamma^2 \varpi^2)} > \frac{\sqrt{q^2 + 1}}{q} \sin^2 \theta$  $q = \frac{\omega_B \lambda \sin^2 \theta}{2\omega \gamma^3 (1 - \cos \theta v_{\parallel}/c)^2 (\cos \theta - v_{\parallel}/c)}$  $K_i^{-1} = i \frac{E_x}{E_y} = q \pm \sqrt{1 + q^2}$ 

q >> 1 (K = 2q, 1/2q) – linear polarization

 $q \ll 1 \ (K = +1, -1) - \text{circular polarization}$ 

# Results

Yu. A.Kravtsov, Yu.I.Orlov (1990)

$$\varepsilon_{ij} = \varepsilon \delta_{ij} + \chi_{ij}$$

$$\frac{\mathrm{d}\Theta}{\mathrm{d}\sigma} = \kappa + \frac{i\omega}{4c} [(\chi_{b\nu} - \chi_{\nu b}) + (\chi_{b\nu} + \chi_{\nu b})\cos 2\Theta - (\chi_{\nu\nu} - \chi_{bb})\sin 2\Theta]$$

$$\Theta = \theta_1 + i\theta_2$$

$$\frac{\mathrm{d}\theta_1}{\mathrm{d}r} = -\frac{1}{2}\frac{\omega}{c}\frac{\Delta n}{\sqrt{q^2+1}} + \frac{1}{2}\frac{\omega}{c}\cos[2\theta_1 - 2\beta(r)]\frac{\Delta nq}{\sqrt{q^2+1}}\mathrm{sh}2\theta_2,$$
  
$$\frac{\mathrm{d}\theta_2}{\mathrm{d}r} = -\frac{1}{2}\frac{\omega}{c}\frac{\Delta nq}{\sqrt{q^2+1}}\sin[2\theta_1 - 2\beta(r)]\mathrm{ch}2\theta_2.$$

Yu. A.Kravtsov, Yu.I.Orlov (1990)

$$\frac{\mathrm{d}\theta_1}{\mathrm{d}r} = -\frac{1}{2}\frac{\omega}{c}\frac{\Delta n}{\sqrt{q^2+1}} + \frac{1}{2}\frac{\omega}{c}\cos[2\theta_1 - 2\beta(r)]\frac{\Delta nq}{\sqrt{q^2+1}}\mathrm{sh}2\theta_2,$$
  
$$\frac{\mathrm{d}\theta_2}{\mathrm{d}r} = -\frac{1}{2}\frac{\omega}{c}\frac{\Delta nq}{\sqrt{q^2+1}}\sin[2\theta_1 - 2\beta(r)]\mathrm{ch}2\theta_2.$$

Gives the direct information about the polarization of outgoing radiation

$$\theta_1 = \beta, \quad \beta + \pi/2,$$
  
 $\operatorname{sh} 2\theta_2 = \pm \frac{1}{q}, \quad |\operatorname{th} \theta_2| = K.$ 

Yu. A.Kravtsov, Yu.I.Orlov (1990)

$$\frac{\mathrm{d}\theta_1}{\mathrm{d}r} = -\frac{1}{2}\frac{\omega}{c}\frac{\Delta n}{\sqrt{q^2+1}} + \frac{1}{2}\frac{\omega}{c}\cos[2\theta_1 - 2\beta(r)]\frac{\Delta nq}{\sqrt{q^2+1}}\mathrm{sh}2\theta_2,$$
  
$$\frac{\mathrm{d}\theta_2}{\mathrm{d}r} = -\frac{1}{2}\frac{\omega}{c}\frac{\Delta nq}{\sqrt{q^2+1}}\sin[2\theta_1 - 2\beta(r)]\mathrm{ch}2\theta_2.$$

Ordinary wave –  $\theta_1 = \beta(r)$ Extraordinary wave –  $\theta_1 = \beta(r) + \pi/2$ 

Yu. A.Kravtsov, Yu.I.Orlov (1990)

$$\frac{\mathrm{d}\theta_1}{\mathrm{d}r} = -\frac{1}{2}\frac{\omega}{c}\frac{\Delta n}{\sqrt{q^2+1}} + \frac{1}{2}\frac{\omega}{c}\cos[2\theta_1 - 2\beta(r)]\frac{\Delta nq}{\sqrt{q^2+1}}\mathrm{sh}2\theta_2,$$
  
$$\frac{\mathrm{d}\theta_2}{\mathrm{d}r} = -\frac{1}{2}\frac{\omega}{c}\frac{\Delta nq}{\sqrt{q^2+1}}\sin[2\theta_1 - 2\beta(r)]\mathrm{ch}2\theta_2.$$

If the shear of the magnetic field is large, and  $\omega_{\rm B} > \gamma \overline{\omega}$ 

$$\theta_2 \approx -\frac{1}{2|q|} \cdot \frac{\mathrm{d}\beta/\mathrm{d}x}{|v_{\parallel}/c - \cos\theta|} \cos[2\theta_1 - 2\beta(r)], \qquad x = \Omega r/c$$

The sign of the circular polarization is determined by  $d\beta / dx$ 

Yu. A.Kravtsov, Yu.I.Orlov (1990)

#### The Key point

If the shear of the magnetic field is large, and  $\omega_{\rm B} > \gamma \overline{\omega}$ 

$$\theta_2 \approx -\frac{1}{2|q|} \cdot \frac{\mathrm{d}\beta/\mathrm{d}x}{|v_{\parallel}/c - \cos\theta|} \cos[2\theta_1 - 2\beta(r)], \quad x = \Omega r/c$$

The sign of the circular polarization is determined by  $d\beta / dx$ 





 $lg(r/R_L)$ 

## Two main theoretical results

- For originally fully polarized mode it is enough to solve TWO equations, not FOUR.
- For high enough shear of the external magnetic field the circular polarization is given by well-determined diagonal components of the dielectric tensor.

As a result, we can recognize the mode!

#### Core & Conal

Profile	$O_S$	$O_D$	$X_S$	$X_D$
Number	6	23	45	6
$\sqrt{P}W_{50}$	$6.8 \pm 3.1$	$10.7 \pm 4.5$	$6.5\pm~2.9$	$5.3\pm$ $3.0$

P.Weltevrede, S.Johnston. MNRAS, **391**, 1210 (2008) T.Hankins, J.Rankin. Astron. J., **139**, 168 (2010)

$$\begin{split} W^{(1)} &\approx 3.6^{\circ} \left(\frac{P}{1 \, s}\right)^{-3/4} \left(\frac{\nu}{1 \, \text{GHz}}\right)^{-1/2} \left(\frac{\lambda}{10^4}\right)^{1/8} \left(\frac{B}{10^{12} \text{G}}\right)^{1/8} \left(\frac{\gamma}{100}\right)^{7/8}, \\ W^{(2)} &\approx 7.8^{\circ} \left(\frac{P}{1 \, s}\right)^{-0.43} \left(\frac{\nu}{1 \, \text{GHz}}\right)^{-0.14} \left(\frac{\lambda}{10^4}\right)^{0.07} \left(\frac{B}{10^{12} G}\right)^{0.07} \left(\frac{\gamma}{100}\right)^{-0.11}, \\ W^{(2)} &\approx 10^{\circ} \left(\frac{P}{1 \, s}\right)^{-0.5} \left(\frac{\nu}{1 \, \text{GHz}}\right)^{-0.29} \left(\frac{\lambda}{10^4}\right)^{0.1} \left(\frac{B}{10^{12} \text{G}}\right)^{0.1} \left(\frac{\gamma}{100}\right)^{-0.05}. \end{split}$$

### Statement #6

# Cyclotron absorption can form mean profile

#### Main result

- For ordinary wave (conal) the signs
   dp.a./dφ and V are to be opposite, and for
   the extraordinary wave (core) are to be the same.
- This property depends neither on the sign  $\Omega m$ , nor on the pole of the neutron star.

O-mode is to be wider (and mainly D) X-mode is to be narrower (and mainly S)

#### First step (7 years ago) A.S.Andrianov, VB. Astron. Lett. **36**, 248 (2010)

- Simple model of the dielectric tensor
- Simple model of magnetic field
- No refraction
- No aberration
- No electric drift

#### Core & Conal

Profile	$O_S$	$O_D$	$X_S$	$X_D$
Number	6	23	45	6
$\sqrt{P}W_{50}$	$6.8 \pm 3.1$	$10.7 \pm 4.5$	$6.5\pm~2.9$	$5.3\pm$ $3.0$

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#### Second step (5 years ago) VB, A.A.Philippov, MNRAS, **425**, 814 (2012)

We included into consideration

- The electric drift
- Arbitrary magnetic field structure
- Arbitrary number density cross section
- Arbitrary particle energy distribution function

#### Equations – no drift



#### Dielectric tensor – no drift



 $\varpi = \omega - k_x v_{\parallel}$ 

#### Dielectric tensor with drift

$$\begin{split} \varepsilon_{xx} &= 1 - < \frac{k_z^2 U_x^2 \omega_p^2}{\tilde{\omega}^2 \gamma^3 \omega^2 (1 - U^2 / c^2)} > + < \frac{\omega_p^{\epsilon} (\tilde{\omega}_p^{\epsilon} + \frac{-c_z^2}{c_z^2} (\frac{1 - U^2 / c^2}{1 - U^2 / c^2} - \omega^2))\gamma}{\omega^2 (\omega_B^2 (1 - U^2 / c^2) - \gamma^2 \tilde{\omega}^2)} > + < \frac{\omega_p^2 (\tilde{\omega}_0 k_x U_y + \frac{U_x U_y}{c^2} (\frac{(k_z v_{\parallel})^2}{1 - U^2 / c^2} - \omega^2))\gamma}{\omega^2 (\omega_B^2 (1 - U^2 / c^2) - \gamma^2 \tilde{\omega}^2)} > + < \frac{\omega_p^2 (\tilde{\omega}_0 - \omega U^2 / c^2)}{\omega^2 (\omega_B^2 (1 - U^2 / c^2) - \gamma^2 \tilde{\omega}^2)} > + < \frac{\omega_p^2 (\tilde{\omega}_0 - \omega U^2 / c^2)}{\omega^2 (\omega_B^2 (1 - U^2 / c^2) - \gamma^2 \tilde{\omega}^2)} > + < \frac{\omega_p^2 (\tilde{\omega}_0 - \omega U^2 / c^2) \gamma (k_x - \omega U_x / c^2) + \frac{U_y^2}{c_z^2} k_z k_x v_{\parallel}^2)\gamma}{\omega^2 (\omega_B^2 (1 - U^2 / c^2) - \gamma^2 \tilde{\omega}^2)} > + < \frac{\omega_p^2 ((\tilde{\omega}_0 - \omega U^2 / c^2) v_{\parallel} (k_x - \omega U_x / c^2) + \frac{U_y^2}{c_z^2} k_z k_x v_{\parallel}^2)\gamma}{(1 - U^2 / c^2) - \gamma^2 \tilde{\omega}^2)} > -i < \frac{\omega_B \omega_p^2}{\omega (\omega_B^2 (1 - U^2 / c^2) - \gamma^2 \tilde{\omega}^2)} \frac{U_x v_{\parallel}}{c^2} >, \\ \varepsilon_{yy} &= 1 - < \frac{k_z^2 U_y^2 \omega_p^2}{\tilde{\omega}^2 \gamma^3 \omega^2 (1 - U^2 / c^2)} > + < \frac{\omega_p^2 ((\tilde{\omega}_x - \omega U_x / c^2) + \frac{U_y^2}{c^2} (\frac{(k_z v_{\parallel})^2}{1 - U^2 / c^2} - \omega^2) + (k_x^2 U_y^2))\gamma}{\omega^2 (\omega_B^2 (1 - U^2 / c^2) - \gamma^2 \tilde{\omega}^2)} >, \\ \varepsilon_{zz} &= 1 - < \frac{\omega_p^2 (1 - \frac{k_x U_x}{\omega})^2}{\tilde{\omega}^2 \gamma^3 (1 - U^2 / c^2)} > + < \frac{\omega_p^2 ((k_x c - \omega U_x / c)^2 + \frac{U_y^2}{c^2} (\omega^2 - (k_x c)^2))\gamma}{\omega^2 (\omega_B^2 (1 - U^2 / c^2) - \gamma^2 \tilde{\omega}^2)} \frac{v_{\parallel}^2 / c^2}{1 - U^2 / c^2} >, \\ \varepsilon_{yz} &= - < \frac{k_z U_y \omega_p^2 (\omega - k_x U_x)}{\tilde{\omega}^2 \gamma^3 \omega^2 (1 - U^2 / c^2)} > + < \frac{\omega_p^2 ((k_x^2 c^2 - \omega^2) (1 - U^2 / c^2) + k_z v_{\parallel} (\omega - k_x U_x))\gamma}{\omega^2 (\omega_B^2 (1 - U^2 / c^2) - \gamma^2 \tilde{\omega}^2)} \frac{v_{\parallel} / c^2}{1 - U^2 / c^2} >, \\ \varepsilon_{yz} &= - < \frac{k_z U_y \omega_p^2 (\omega - k_x U_x)}{\tilde{\omega}^2 \gamma^3 \omega^2 (1 - U^2 / c^2)} > + < \frac{\omega_p^2 ((k_x^2 c^2 - \omega^2) (1 - U^2 / c^2) + k_z v_{\parallel} (\omega - k_x U_x))\gamma}{\omega^2 (\omega_B^2 (1 - U^2 / c^2) - \gamma^2 \tilde{\omega}^2)} \frac{v_{\parallel} / c^2}{1 - U^2 / c^2} >, \\ \varepsilon_{yz} &= - < \frac{k_z U_y \omega_p^2 (\omega - k_x U_x)}{\tilde{\omega}^2 \gamma^3 \omega^2 (1 - U^2 / c^2)} > + < \frac{\omega_p^2 ((k_x^2 c^2 - \omega^2) (1 - U^2 / c^2) + k_z v_{\parallel} (\omega - k_x U_x))\gamma}{\omega^2 (\omega_B^2 (1 - U^2 / c^2) - \gamma^2 \tilde{\omega}^2)} \frac{v_{\parallel} / c^2}{1 - U^2 / c^2} > -i < \\ \frac{\omega_y \omega_p^2 (\omega - k_x U_x)}{\omega^2 (\omega - k_$$

#### Equations with drift

$$\frac{\mathrm{d}\Theta_1}{\mathrm{d}l} = \frac{\omega}{2c} \mathrm{Im}[\varepsilon_{x'y'}] \\ -\frac{1}{2}\frac{\omega}{c}\Lambda\cos[2\Theta_1 - 2\beta(l) - 2\delta(l)]\sinh 2\Theta_2, \\ \frac{\mathrm{d}\Theta_2}{\mathrm{d}l} = \frac{1}{2}\frac{\omega}{c}\Lambda\sin[2\Theta_1 - 2\beta(l) - 2\delta(l)]\cosh 2\Theta_2.$$

$$\Lambda = \mp \sqrt{(\operatorname{Re}[\varepsilon_{x'y'}])^2 + \left(\frac{\varepsilon_{x'x'} - \varepsilon_{y'y'}}{2}\right)^2}$$

$$\tan(2\delta) = -\frac{2\operatorname{Re}[\varepsilon_{x'y'}]}{\varepsilon_{y'y'} - \varepsilon_{x'x'}} \qquad \tan(\delta) = -\frac{\cos\theta \, U_y/c}{\sin\theta - U_x/c}$$

#### Important comment

In the first paper by<br/>Andrianov & VB $\frac{d\Theta_2}{dl}$ •V had 'wrong' sign<br/>(different determination), tan( $\delta$ )2. Drift ( $\delta$ ) was not<br/>included into consideration...

Historical anecdote

In reality we have one-to-one correspondence between  $d\beta_B/dl$   $dp.a./d\phi$  and

C.Wang et al. MNRAS, **417**, 1183 (2011)



#### Magnetic field structure



# Spitkovsky, poloidal field, $\chi = 60^{\circ}$



#### Plasma profile

Arbitrary 2D (axisymmetric) profile



 $n_{\rm e}(\theta_{\rm m},\varphi_{\rm m}) = \lambda g(\theta_{\rm m},\varphi_{\rm m}) n_{\rm GJ}$ 

#### **Back integration**



Good agreement between numerical simulation and analytic result!

 $\rho = \frac{1}{R_0/R} \frac{\sin \theta_m}{\sqrt{r/R}}$ 

#### **Energy distribution function**


#### "Core-conal" model



# Wrong fit

VB, A.A.Philippov, MNRAS, 425, 814 (2012)



Second step (5 years ago) VB, A.A.Philippov, MNRAS, **425**, 814 (2012)

Main results

- Shift *p.a.* curve to the right
- Flat *p*.*a*. curve for small *P*
- Generally, the trailing part is to be absorbed
- RVM is too unclear

# Third step (4 years ago)

P.Jaroenjittichai, A.A.Philippov, VB, M.Kramer. MNRAS (submitted)

Full statistics Pulsars with a flat *p.a.* O-X-O for triple profiles

### Core & Conal

Modes/Types	Counts	Mode	es/Types	Counts
Xs Xd Xt,m Total X	7 - 1 8	Xs Xd Xt,m X? or	• ?X or ?X?	27 8 12
Os Od Ot m	3 8 3	Total Os	X	47 10
Total O	14	Od Ot,m O? or	?O or ?O?	14 4 8
$\begin{array}{l} \mathrm{Xs} \to \mathrm{Os} \\ \mathrm{Xd} \to \mathrm{Od} \end{array}$	$\frac{4}{2}$	Total	0	36
Total mix	6	Total	mix	21

T.Hankins, J.Rankin Astron. J., **139**, 168 (2010) P.Weltevrede, S.Johnston MNRAS **391**, 1210 (2008)

### Third step (4 years ago)

P.Jaroenjittichai, A.A.Philippov, VB, M.Kramer. MNRAS (submitted)

Pulsars with flat *p.a.* 

$$r_{\rm esc}/R_{\rm L} \propto P^{-6/5} \nu^{-2/5}$$

**Table 5.** Pulsars with almost constant p.a. Here P  $\dot{P}$  is in  $10^{-15}$ , and magnetic field B on the surface c is in  $10^{12}$  G

PSR	P(s)	<i>P</i>	$B_{12}$	comment
J0543+2329	0.25	15.4	2.0	+
J0738-4042	0.37	1.6	0.8	+
J0837-4135	0.75	3.5	1.6	
J1559-4438	0.26	1.0	0.5	+
J1735-0724	0.42	1.2	0.7	
B1907-03	0.50	2.2	1.0	
J1915+1009	0.40	1.5	2.5	
J1937+2544	0.20	0.6	0.4	+

## More pulsars with flat p.a.

A.Noutsos et al (LOFAR) A&A, 576, 62 (2015)

Pulsars with flat *p.a.* 

$$r_{\rm esc}/R_{\rm L} \propto P^{-6/5} \nu^{-2/5}$$



P = 0.0018 s

P = 0.27 s P = 0.00525 s

## Third step (4 years ago)

P.Jaroenjittichai, A.A.Philippov, VB, M.Kramer. MNRAS (submitted)

Very negative referee's reply, the paper was rejected. *There are some contradicting examples:* 

J0452-1759

J0738-4042

J2048-1616



# Forth step (now)

VB, H.Hakobyan, A.Philippov

More statistics and individual pulsars Generalization

- Asymmetric number density
- Longitudinal current density
- **General properties**
- Shift to the right
- .p.a. hump for double profiles
- Generation level diagnostics
- Individual pulsars
- Determination of the inclination angle

#### O-X-O

#### Bad example





**Figure 2.** The plot of  $\beta + \delta$  along the propagation ray. If the polarization is formed below the extremum, the sign is governed by the derivative of  $\beta_B$ , and when it's formed above - the sign is determined by the derivative of  $\delta$  (Paper I).

**Figure 3.** The profile for a pulsar with high  $\gamma_0$ . In this case for difference phases  $\phi = -5^\circ$  and  $\phi = 5^\circ$  the circular polarization has different signs, due to the variation of the escape radius with respect to the extremum of  $\beta_B$  + (see Fig. 2).

#### PSR J0452-1759



#### PSR J0738-4042



#### PSR J2048-1616



### *p.a.* hump for double profiles

A.Noutsos et al. A&A, **576**, 62 (2015)



Figure 4. Simulated profile for PSR J1022-1001 at 728 MHz in comparison with observational data from Dai et al. (2015).

## *p.a.* hump for double profiles

Another examples

A.Noutsos et al A&A, 576, 62 (2015)



# Interpulse



## Interpulse

M.Keith et al, MNRAS, 402, 745 (2010)





#### J1722-3712



## Interpulse

M.Keith et al, MNRAS, 402, 745 (2010)





#### J1739-2903



### p.a. curve width

#### O-mode





## p.a. curve width

#### X-mode





## p.a. frequency dependence





 $\lambda = 10000$ 

#### Main results

- One-to-one correspondence between the signs V and dp.a./dφ. For the X-mode the signs should be the SAME, and the OPPOSITE for the O-mode.
- For central passage the V sign reversal in the core can occur.
- The standard S-shape form of the *p.a.* swing can be realized for small enough multiplicity and large enough bulk Lorentz-factor only.
- In general, the trailing side of the emission beam is absorbed. Leading part can be absorped when the polarization forms close to the light cylinder.
- Electric drift changes the sign of the effect.

# **Conclusion**

- Nature gives us no clean experiment
- Numerous hints were insufficient to clarify the mechanism of radio emission