The influence of small scale magnetic field on the polar cap X-ray luminosity of old radio pulsars

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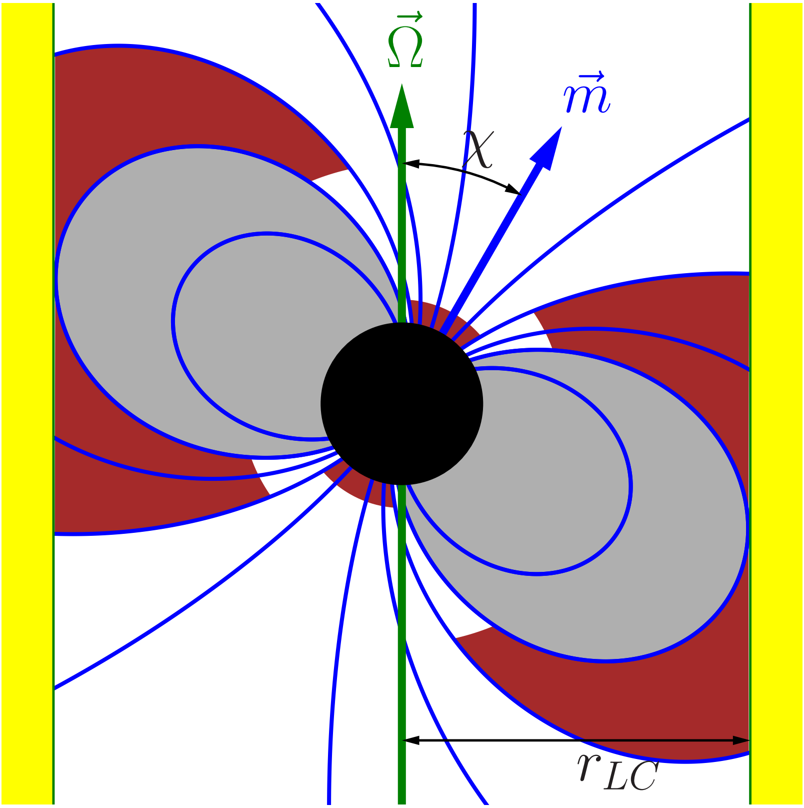
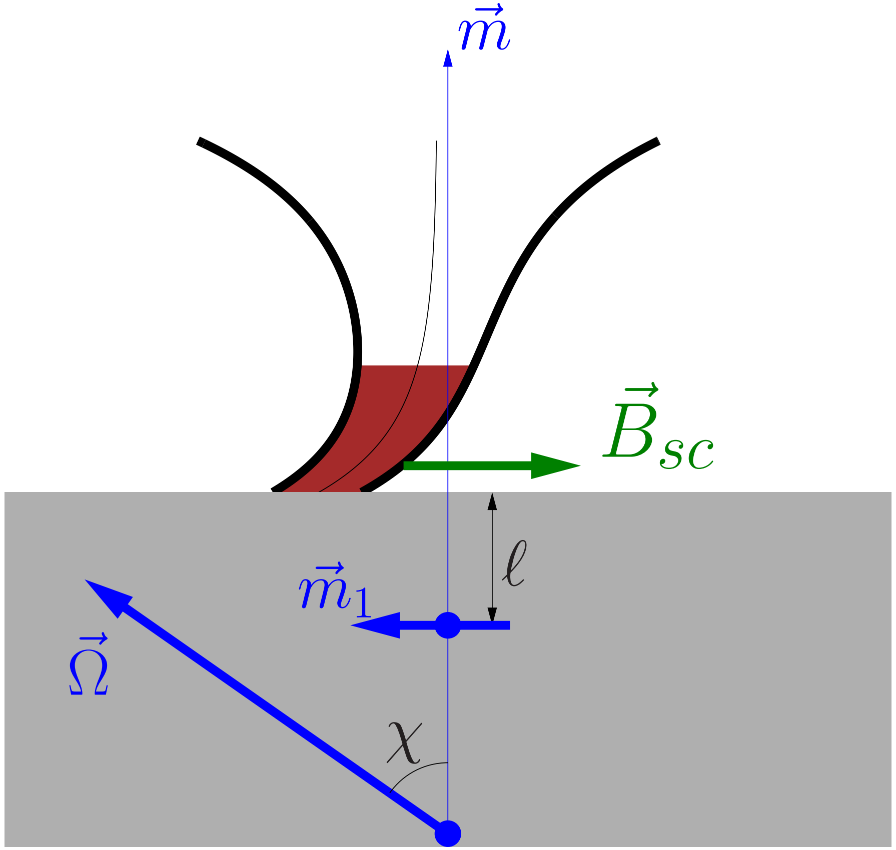
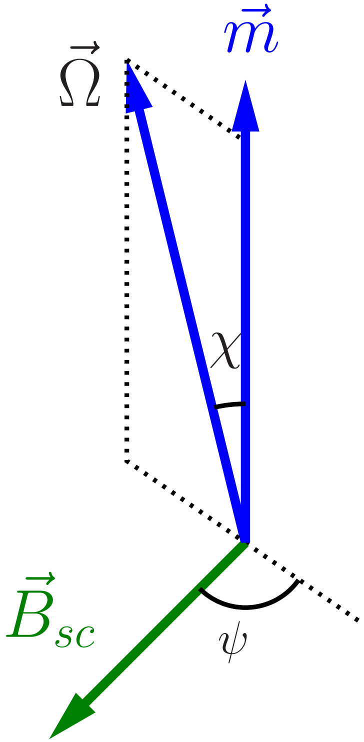


1. **Old isolated radiopulsars**
   $B_{dip} \sim 10^{11} - 10^{12} G$
   $P \sim 100ms - 1s$
   $\tau = P/(2\dot{P}) \gtrsim 10^6$ years
2. **Goldreich-Julian model**
3. **inner gaps**
4. **free electron emission from neutron star surface**
   small surface magnetic field
   $B_{surf} < 10^{13} G$
   hot polar caps $T \sim (1-3) \cdot 10^6 K$
   Z.Medin, D.Lai (2007)
   $\vec{\Omega} \cdot \vec{m} > 0$, $\Omega = \frac{2\pi}{P}$
   $\vec{\Omega}$ is angular velocity of star
5. **no vacuum gaps, no sparks**
   steady space charge limited flow
   W.M.Fawley, J.Arons, E.T.Scharlemann (1977)
6. **stationary case**
7. **only curvature radiation**
   the inverse compton scattering and synchrotron emission do not taken into account
8. **only photon absorption in magnetic field**
   no photon splitting, photon scattering

Small scale magnetic field



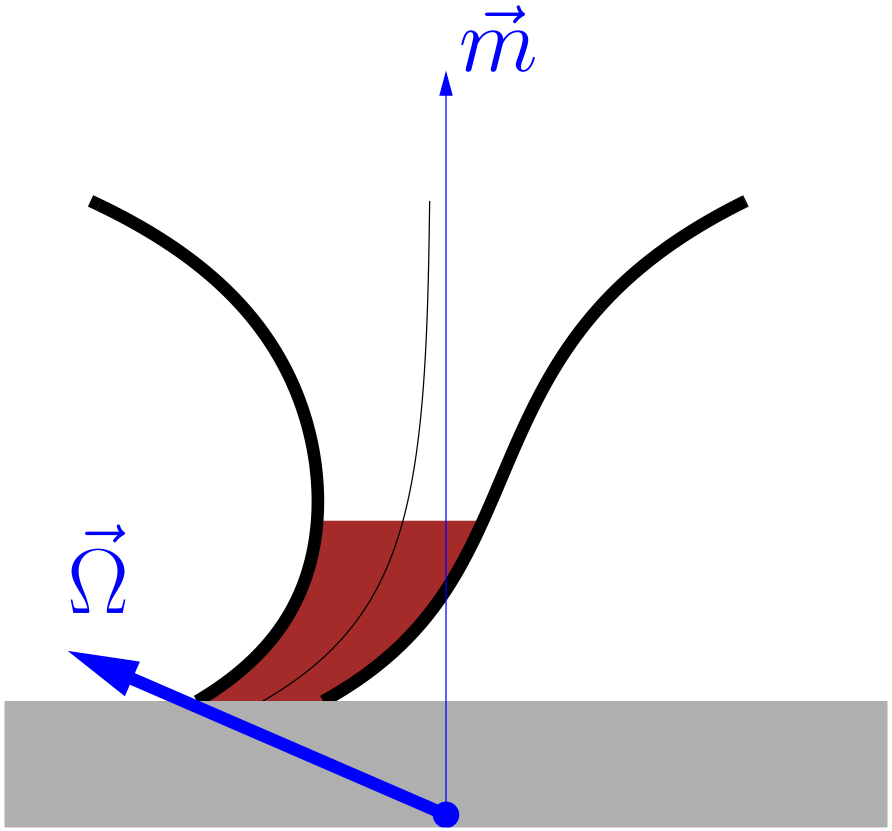


$$\vec{B} = \frac{3\vec{r}\,(\vec{r}\cdot\vec{m}) - \vec{m}r^2}{r^5} + \frac{3\vec{\rho}\,(\vec{\rho}\cdot\vec{m}_1) - \vec{m}_1\rho^2}{\rho^5}$$

$$\vec{\rho} = \vec{r} - (r_{ns} - \ell)\vec{e}_z \qquad \vec{m} = m\vec{e}_z \text{ и } \vec{m}_1 = \nu\left(\frac{\ell}{r_{ns}}\right)^3 m\vec{e}_x$$

$$\ell = \frac{1}{10} r_{ns} \qquad \nu = \frac{B_{sc}}{B_{dip}} \lesssim 1 \qquad 0 \le \psi \le \frac{\pi}{2}$$

Charge density



In the reference frame rotating with the star all values do not depend on time.

$$\Delta\Phi = -4\pi(\rho - \rho_{GJ}), \quad \vec{E} = -\vec{\nabla}\Phi$$

ρ_{GJ} – Goldreich-Julian density

$$\rho = \frac{\Omega B}{2\pi c}\tilde{\rho} \quad \text{and} \quad \rho_{GJ} = -\frac{\Omega B}{2\pi c}\tilde{\rho}_{GJ}$$

$\Omega = 2\pi/P$ is angular velocity of neutron star, B is magnetic field strenght
Particles move along field lines $\vec{v} \parallel \vec{B}$
with relativistic velocity $v \approx c$

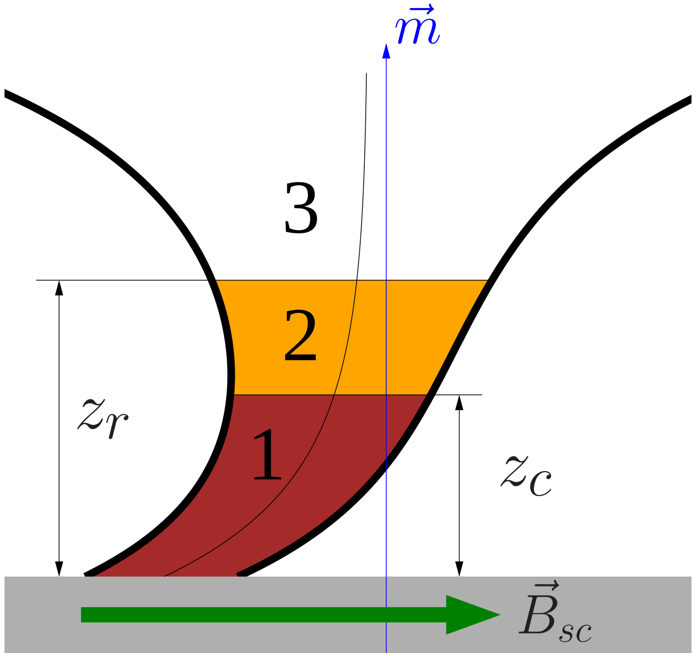
$$\mathrm{div}\,(\rho\vec{v}) = 0 \quad => \quad (\vec{B}\cdot\vec{\nabla})\tilde{\rho} = 0$$

without frame dragging

$$\tilde{\rho}_{GJ}(z) \approx \cos\tilde{\chi}$$

$\tilde{\chi}$ is the angle between $\vec{B}$ and $\vec{\Omega}$

Rapid screening model



J.Arons, E.T.Scharlemann
ApJ **231** 854 (1979)

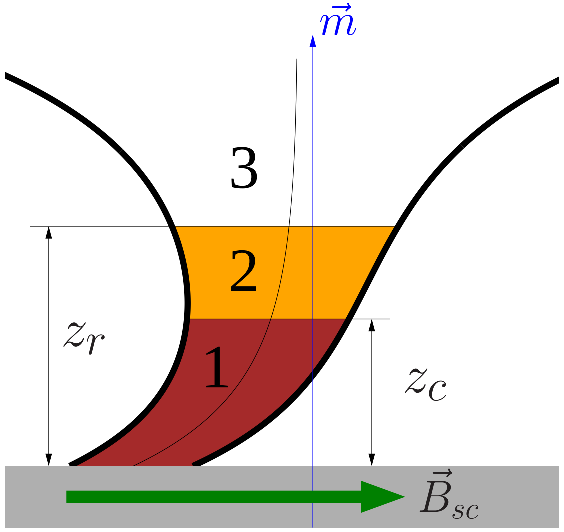
1. $0 < z < z_c$ acceleration region
   no pairs production, no pair plasma
   large $E_{||} = (\vec{E} \cdot \vec{B})/B$
2. $z_c < z < z_r$ partial screening area
   pair plasma, small $E_{||}$
   positrons return to the polar cap
3. $z > z_r$ full screening area
   pair plasma, $E_{||} = 0$
   no positrons return

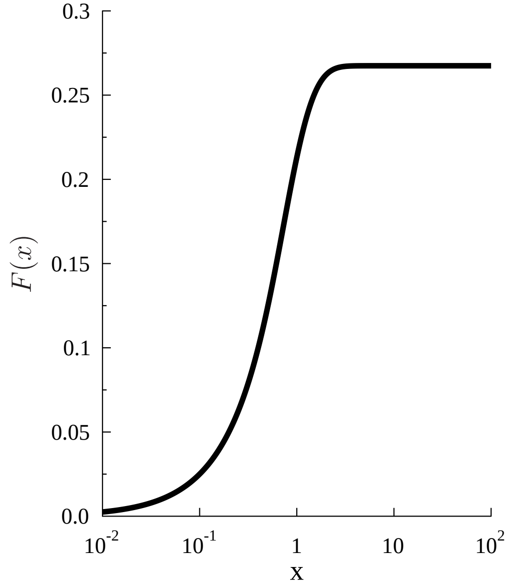
Condition

(a) $E_{||}\Big|_{z=z_r} = 0$
electric field is continous

(b) $(\vec{B} \cdot \vec{\nabla})E_{||}\Big|_{z=z_r} = 0$
charge density is continous

Rapid screening model





pairs are generated by curvature radiation

$z_r - z_c \ll r_t, z_c$

at $r_t \ll \ell$ at the central line the reverse positron current density may be estimated as

$$\tilde{\rho}_+ \approx r_t \left.\frac{\partial \tilde{\rho}_{GJ}}{\partial z}\right|_{z=z_c} F\left(\frac{z_c}{r_t}\right)$$

where r_t is the pulsar tube radius, z is altitude above star

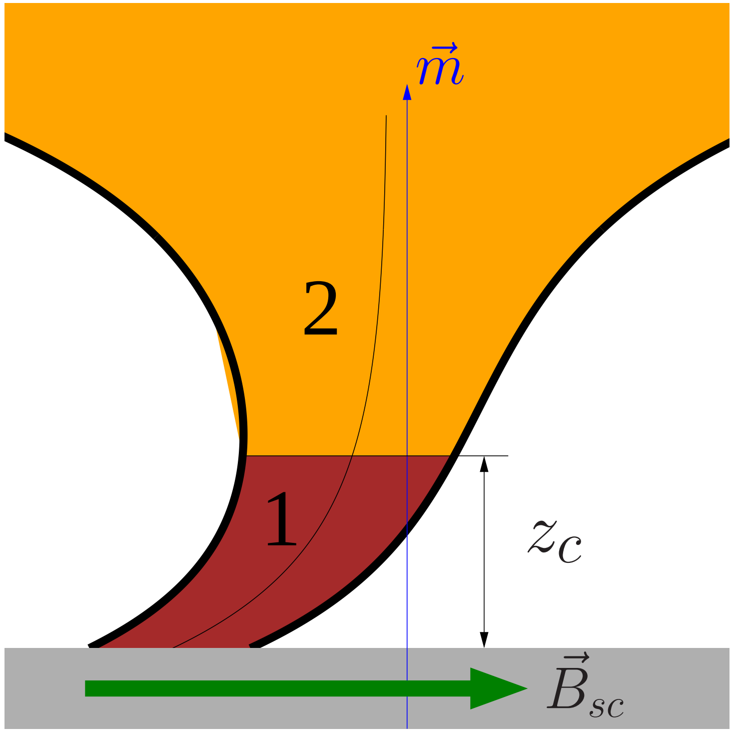
$n_+ = n_{GJ}\tilde{\rho}_+$ – number density of the returning positrons

$n_{GJ} = \frac{\Omega B}{2\pi ce} \approx 7 \cdot 10^{10} cm^{-3} \left(\frac{1s}{P}\right) \left(\frac{B}{10^{12} G}\right)$

$F(x) \approx \frac{4x}{16+15x} \left(1 + 1.19 \frac{x}{1+x^2}\right)$

$F(x) \approx \frac{x}{4}$ at $x \ll 1$, $F(x) \approx \frac{4}{15}$ at $x \gg 1$

Gradual screening model



A.K. Harding, A.G. Muslimov
ApJ **556** 987 (2001)

The assumptions:

- all values do not depend on time t (stationary case)
- pairs are affected only by average electric field
- $\tilde{\rho}_{GJ}$ monotonically grows with the altitude z

Hence, conditions

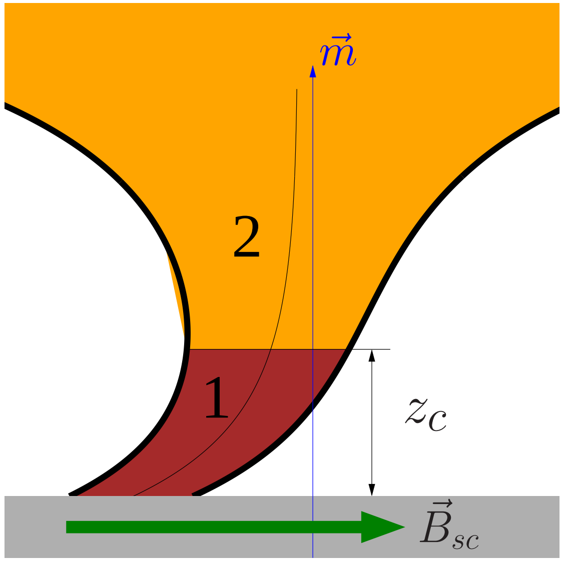
$$E_{||}\Big|_{z=z_r} = 0 \text{ and } (\vec{B}\cdot\vec{\nabla})E_{||}\Big|_{z=z_r} = 0$$

can not be satisfied at the **same** point

No fullscreening area

There is only partial screening area where the electric field is small and $\Phi \to \Phi_\infty$ at $z \to \infty$

Gradual screening model



Yu.E. Lyubarskii
A&A **261** 544 (1992)

Returning current from altitude z_f

$$\tilde{\rho}_+ \approx \frac{1}{2}\left(\tilde{\rho}_{GJ}(z_f) - \tilde{\rho}_{GJ}(z_c)\right)$$

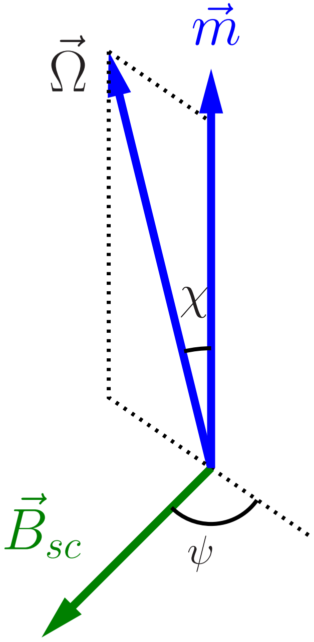
where $n_+ = n_{GJ}\tilde{\rho}_+$ – number density of returning positrons,

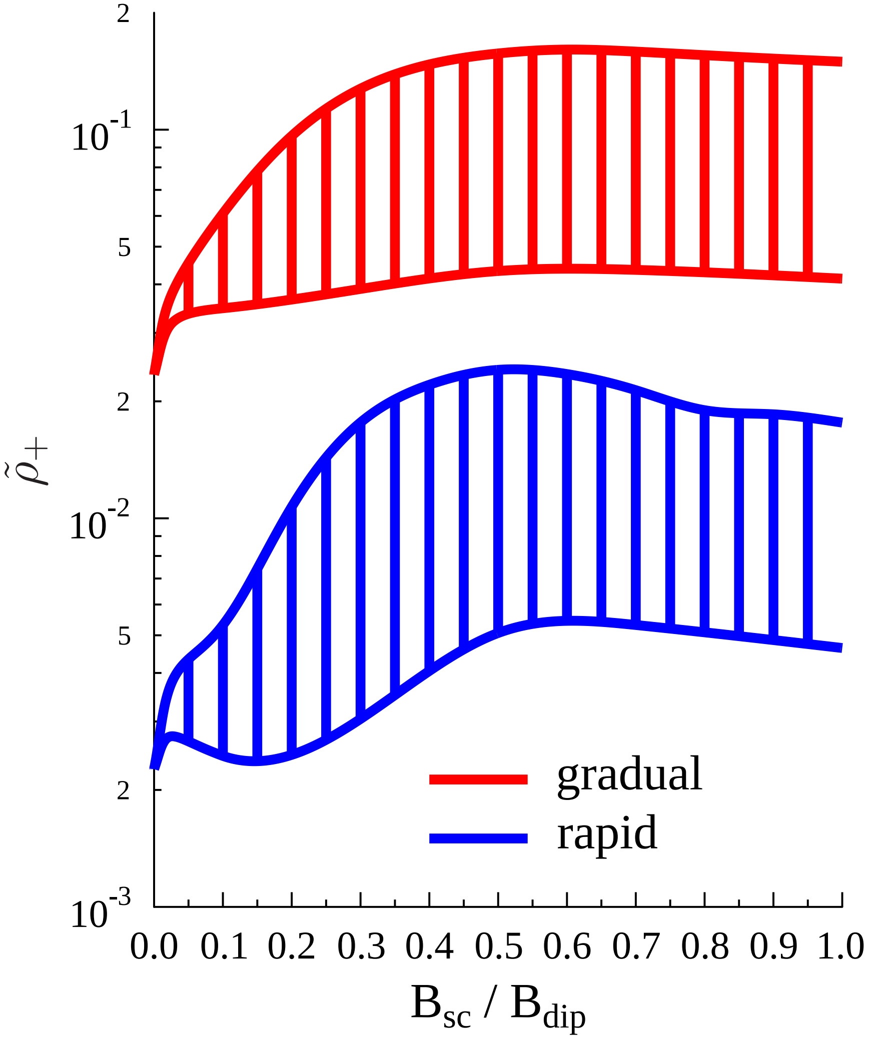
$n_{GJ} = \frac{\Omega B}{2\pi ce} \approx 7 \cdot 10^{10} cm^{-3} \left(\frac{1s}{P}\right)\left(\frac{B}{10^{12}G}\right)$

We suppose $z_f \sim (3-15)r_{ns}$

1. $z_f < z_{rad} \sim (5-50)r_{ns}$
   at large z plasma waves affect on pair dynamics
2. $z_f < z_{max} \sim (1-5)r_{ns}$
   where z_{max} is maximum of $\tilde{\rho}_{GJ}(z)$
   at $z \approx z_{max}$ the solution satisfied both conditions exists
   $E_{||} = 0$ and $(\vec{B} \cdot \nabla)E_{||} = 0$

The reverse positron current for pulsar J2043+2740





rapid: $\tilde{\rho}_+ \sim 10^{-2}$

$\tilde{\rho}_+ \lesssim r_t \frac{\partial \tilde{\rho}_{GJ}}{\partial z}$

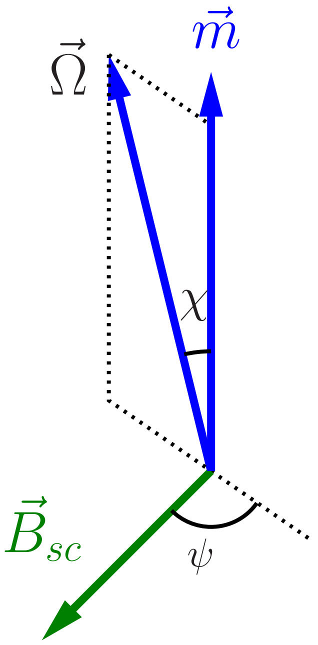
gradual: $\tilde{\rho}_+ \sim 10^{-1}$

$\tilde{\rho}_+ \approx \frac{1}{2} \left(\tilde{\rho}_{GJ}(z_f) - \tilde{\rho}_{GJ}(z_c) \right)$

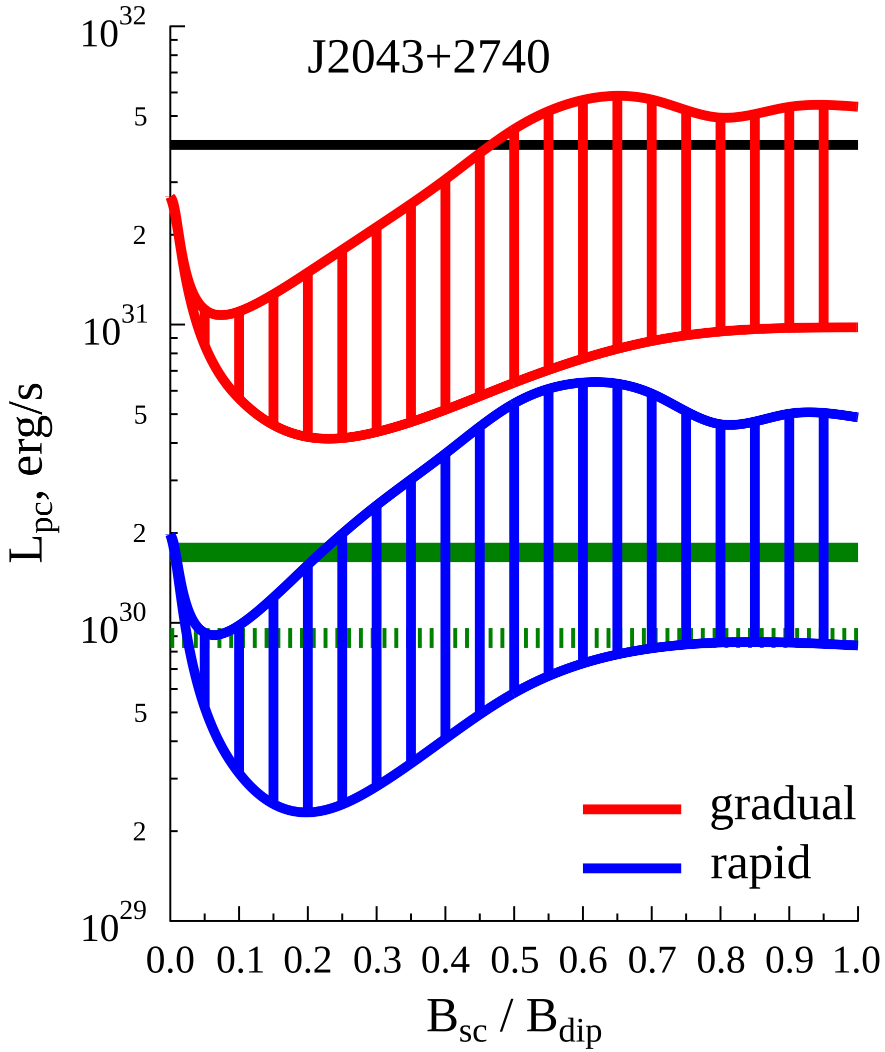
$z_f - z_c \gtrsim r_{ns} \gg r_t$

$B_{dip} = 7.1 \cdot 10^{11} G$, $P = 96 ms$, $\tau = 1.2 \cdot 10^{6}$ years, $\chi = 55^\circ$

The polar cap luminosity for pulsar J2043+2740



$$L_{pc} = \int e\Phi|_{z=z_c} \left.\frac{\Omega B}{2\pi ce}\right|_{z=0} \tilde{\rho}_+ dS$$

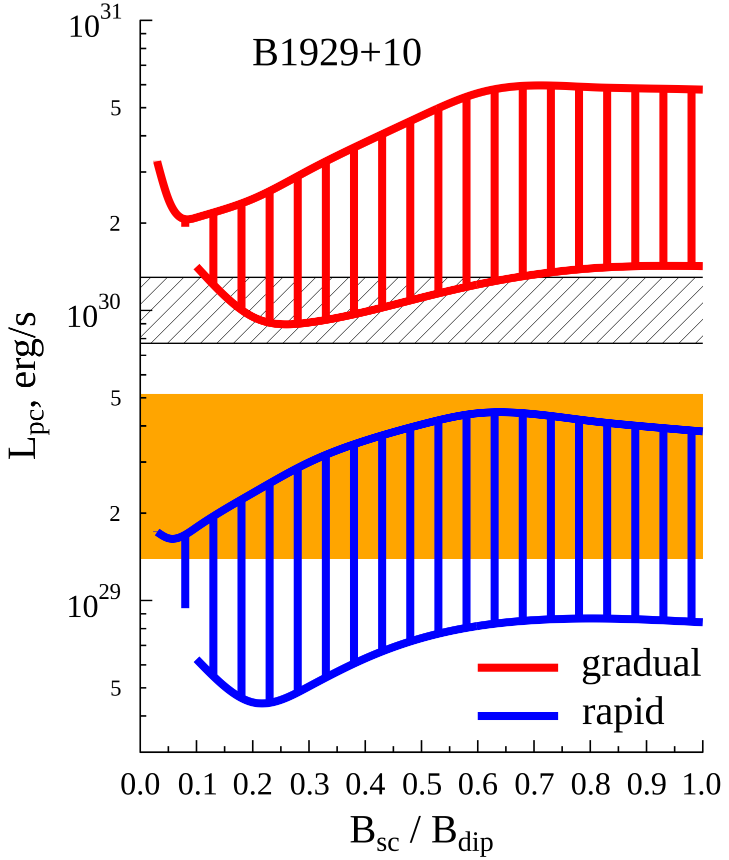


$B_{dip} = 7.1 \cdot 10^{11} G$, $P = 96ms$, $\tau = 1.2 \cdot 10^6$ years, $\chi = 55^\circ$

Upper limits of polar cap emission from W.Becker et al (2004) are shown by green lines, solid when we see one cap, dashed when we see both caps.

Emission of star surface taken from V.E.Zavlin, G.G.Pavlov (2004) is shown by black line.

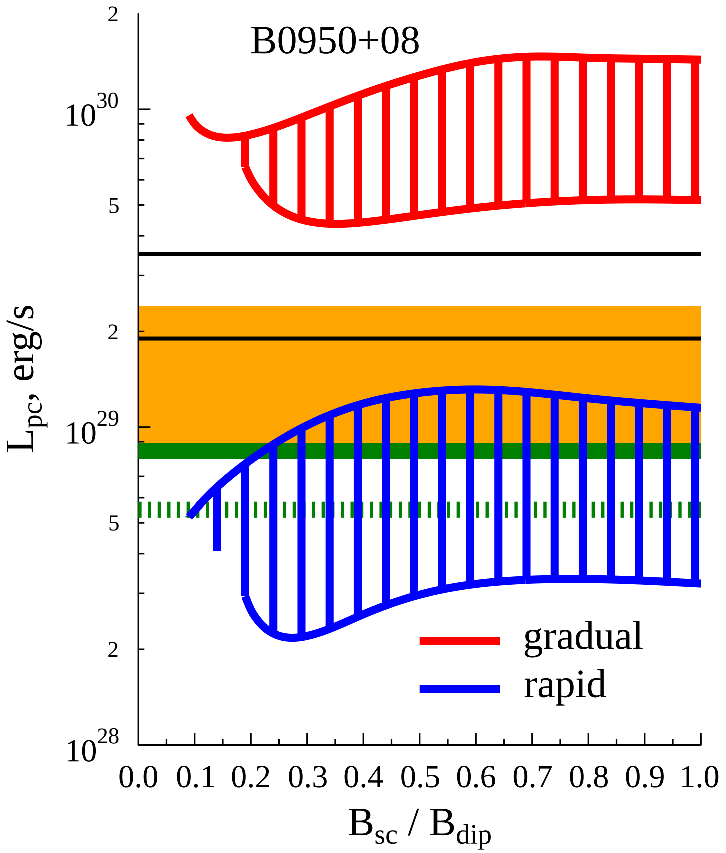
The polar cap luminosity



$B_{dip} = 1.0 \cdot 10^{12} G,\ P = 0.23s$

$\tau = 3 \cdot 10^6$ years, $\chi = 45^\circ$

L_{pc} from Z.Misanovic et al (2008) is shown by orange area. L_{pc} range from J.Gil et al (2008) is shown by black dashed area.

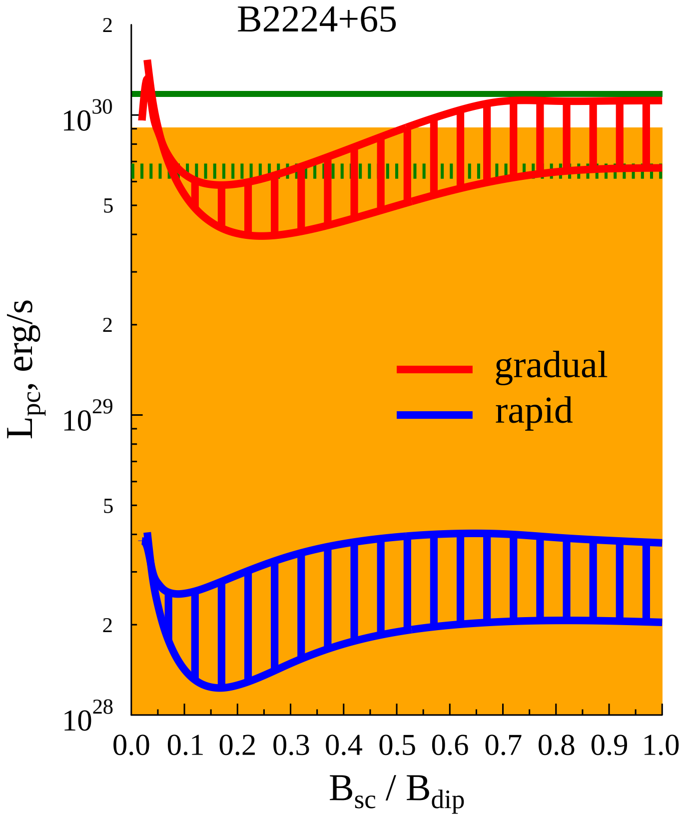


$B_{dip} = 4.9 \cdot 10^{11} G,\ P = 0.25s$

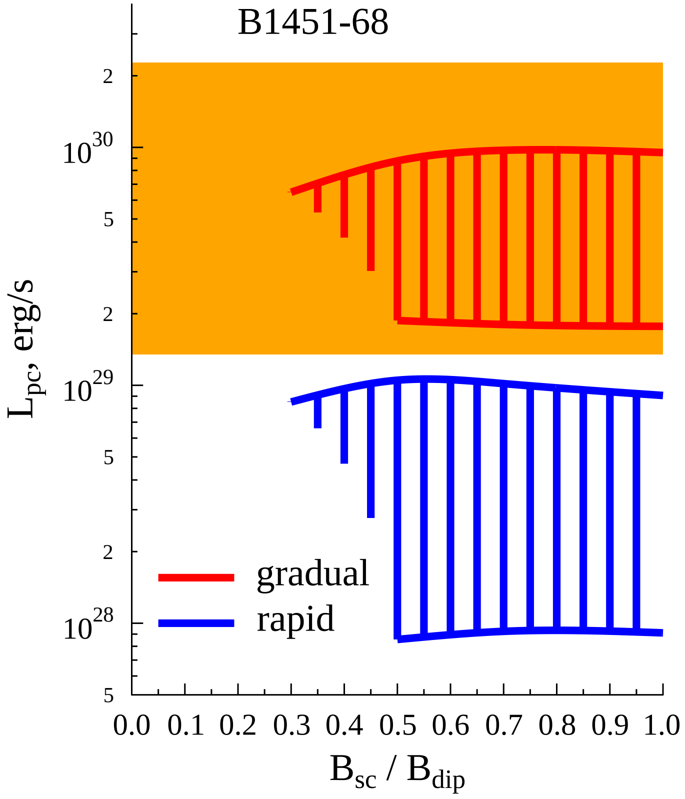
$\tau = 17.5 \cdot 10^6$ years, $\chi = 30^\circ$

L_{pc} from V.E.Zavlin, G.G.Pavlov (2004) is shown by orange area and black lines. Upper limits from W.Becker et al (2004) are shown by green lines, solid when we see one cap, dashed when we see both caps.

The polar cap luminosity



$B_{dip} = 5.2 \cdot 10^{12} G,\ P = 0.68 s$
$\tau = 1.1 \cdot 10^6$ years, $\chi = 16^\circ$
L_{pc} from C.Y.Hui et al (2012) is shown by solid green line. Upper limit from C.Y.Hui,W.Becker (2007) is shown by dashed green line, upper limit from V.E.Zavlin, G.G.Pavlov (2004) is shown by orange area,



$B_{dip} = 3.2 \cdot 10^{11} G,\ P = 0.26 s$
$\tau = 42.5 \cdot 10^6$ years, $\chi = 50^\circ$
L_{pc} from B.Posselt et al (2012) is shown by orange area

Conclusion

For some pulsars the gradual screening model predicts the polar cap heating which is larger than the observed polar cap luminosity.

Possible explanations:

1. Surface magnetic field $B_{surf} > 10^{14} G$
   no free charge emission => vacuum gaps, sparks
2. Large redshift $r_{ns} < 2 r_g$
3. Viscous forces at $z \sim r_t$
   Backflowing radiation
   Radiation locked inside inner gaps

Thank you for your attention