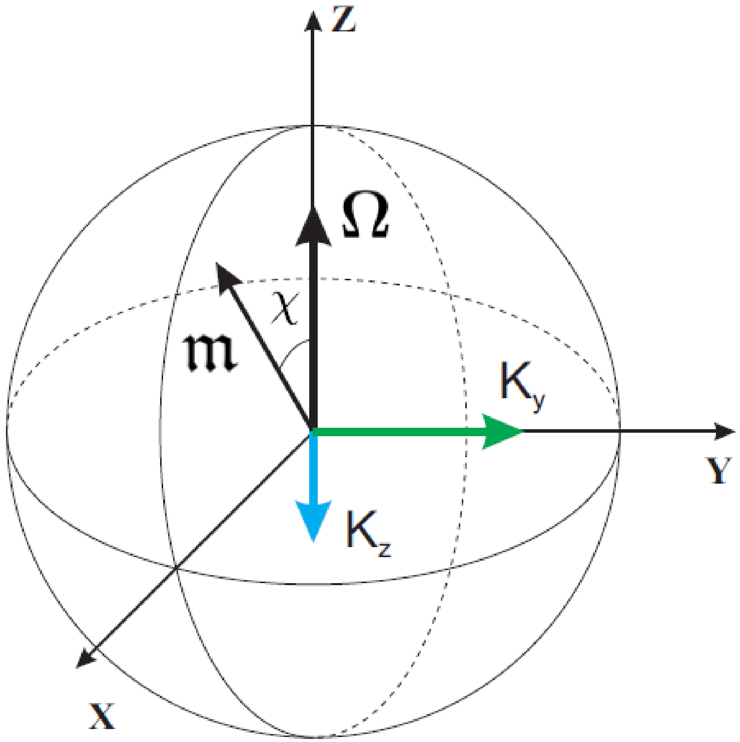
Так как же тормозятся радиопульсары?

В.С. Бескин

ФИАН, МФТИ

Тормозящий момент сил



$$K_{z'} = \frac{2}{3}\frac{\mathfrak{m}^2}{R^3}\left(\frac{\Omega R}{c}\right)^3 \sin^2\chi$$

$$K_{x'} = \frac{2}{3}\frac{\mathfrak{m}^2}{R^3}\left(\frac{\Omega R}{c}\right)^3 \sin\chi\cos\chi$$

$$\boxed{\mathbf{K} = \int \mathbf{r}\times \mathrm{d}\mathbf{F} = \frac{R^3}{4\pi}\int\Big([\mathbf{n}\times\{\mathbf{B}\}]\,(\mathbf{Bn}) + [\mathbf{n}\times\mathbf{E}]\,(\{\mathbf{E}\}\,\mathbf{n})\Big)\mathrm{d}o}$$

Магнито-дипольное излучение

Потери энергии $$W_{\rm tot} = -\mathbf{\Omega}\mathbf{K}$$

$$K_{z'} = \frac{2}{3}\frac{\mathfrak{m}^2}{R^3}\left(\frac{\Omega R}{c}\right)^3 \sin^2\chi$$

$$K_{x'} = \frac{2}{3}\frac{\mathfrak{m}^2}{R^3}\left(\frac{\Omega R}{c}\right)^3 \sin\chi\cos\chi$$

$$\mathbf{K} = \frac{R^3}{c}\int \mathbf{J}_{\rm s}\left(\mathbf{B}\mathbf{n}\right){\rm d}o = \frac{R^3}{4\pi}\int\{[\mathbf{n}\times\mathbf{B}^{(3)}](\mathbf{B}^{(0)}\mathbf{n}) + [\mathbf{n}\times\mathbf{B}^{(0)}](\mathbf{B}^{(3)}\mathbf{n})\}\,{\rm d}o$$

Ландау-Лифшиц, Теория поля

$$
\begin{aligned}
B_r^{\perp} &= \frac{|\mathfrak{m}|}{r^3}\sin\theta\,\mathrm{Re}\left(2-2i\frac{\Omega r}{c}\right)\exp\left(i\frac{\Omega r}{c}+i\varphi-i\Omega t\right),\\
B_\theta^{\perp} &= \frac{|\mathfrak{m}|}{r^3}\cos\theta\,\mathrm{Re}\left(-1+i\frac{\Omega r}{c}+\frac{\Omega^2 r^2}{c^2}\right)\exp\left(i\frac{\Omega r}{c}+i\varphi-i\Omega t\right),\\
B_\varphi^{\perp} &= \frac{|\mathfrak{m}|}{r^3}\,\mathrm{Re}\left(-i-\frac{\Omega r}{c}+i\frac{\Omega^2 r^2}{c^2}\right)\exp\left(i\frac{\Omega r}{c}+i\varphi-i\Omega t\right),\\
E_r^{\perp} &= 0,\\
E_\theta^{\perp} &= \frac{|\mathfrak{m}|\Omega}{r^2 c}\,\mathrm{Re}\left(-1+i\frac{\Omega r}{c}\right)\exp\left(i\frac{\Omega r}{c}+i\varphi-i\Omega t\right),\\
E_\varphi^{\perp} &= \frac{|\mathfrak{m}|\Omega}{r^2 c}\cos\theta\,\mathrm{Re}\left(-i-\frac{\Omega r}{c}\right)\exp\left(i\frac{\Omega r}{c}+i\varphi-i\Omega t\right).
\end{aligned}
$$

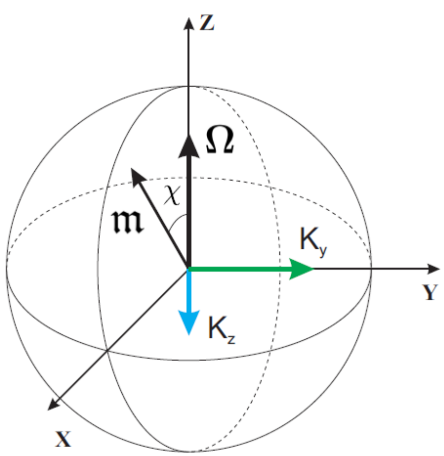
Третий порядок!

Потери энергии

$$\beta_{\mathrm{R}} = \frac{\mathbf{\Omega} \times \mathbf{r}}{c}$$

$$W_{\mathrm{tot}} = \frac{c}{4\pi} \int (\beta_{\mathrm{R}} \mathbf{B})(\mathbf{B} d\mathbf{S})$$

Вакуум	(Л&Л)	(1/3)	1	Ω	1	Ω^3	1	$= \Omega^4$
Вакуум	(Л&Л)	(2/3)	1	Ω	Ω^3	1	1	$= \Omega^4$



$$\boxed{\mathbf{B}^{(3)} = -\frac{2}{3} \frac{\mathfrak{m}}{R^3} \left(\frac{\Omega R}{c} \right)^3 \mathbf{e}_{y'}}$$

Третий порядок!

Потери энергии

$$\beta_{\mathrm{R}} = \frac{\mathbf{\Omega} \times \mathbf{r}}{c}$$

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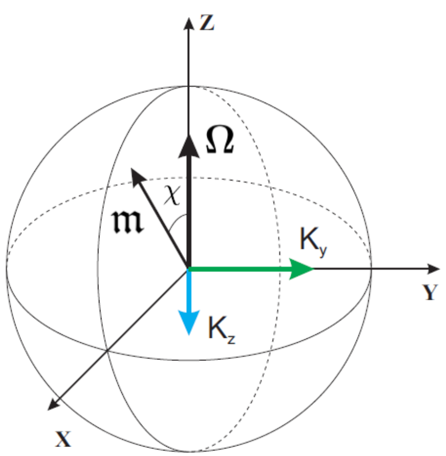
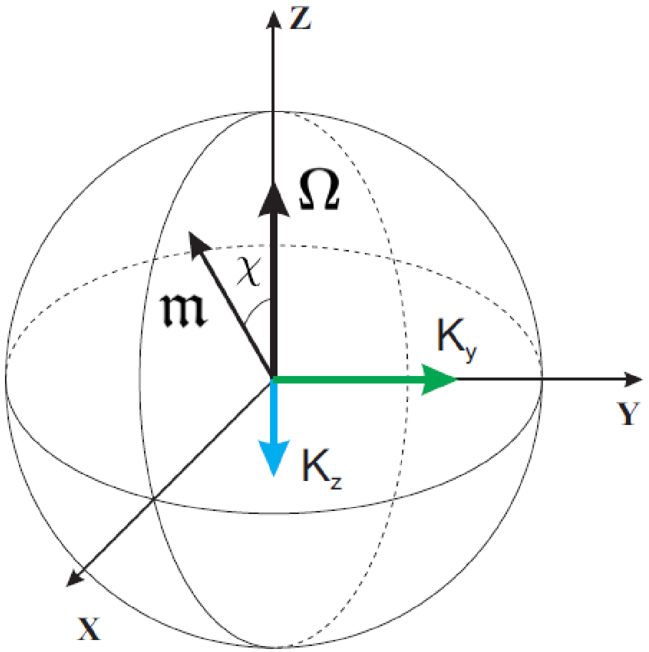
Вакуум (Л&Л) (1/3)	1	Ω	1	Ω^3	1	$= \Omega^4$
Вакуум (Л&Л) (2/3)	1	Ω	Ω^3	1	1	$= \Omega^4$
Вакуум (Deutsch)	1	Ω	Ω^3	1	1	$= \Omega^4$



$$\boxed{\mathbf{B}^{(3)} = -\frac{2}{3} \frac{\mathfrak{m}}{R^3} \left(\frac{\Omega R}{c}\right)^3 \mathbf{e}_{y'}}$$

Вывод

Оба слагаемых могут играть роль!



$$\mathbf{K} = \frac{R^3}{c}\int \mathbf{J}_{\mathrm{s}}\left(\mathbf{B}\mathbf{n}\right)\mathrm{d}o = \frac{R^3}{4\pi}\int \{[\mathbf{n}\times\mathbf{B}^{(3)}](\mathbf{B}^{(0)}\mathbf{n}) + [\mathbf{n}\times\mathbf{B}^{(0)}](\mathbf{B}^{(3)}\mathbf{n})\}\,\mathrm{d}o$$

Ключевая электромагнитная идея

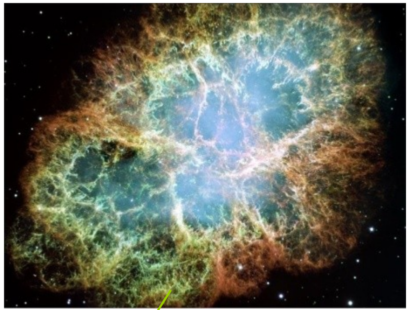
(N.S.Kardashev,1964; F.Pacini, 1967)

Магнито-дипольные потери

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

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

Момент истины



Пульсар в Крабовидной туманности

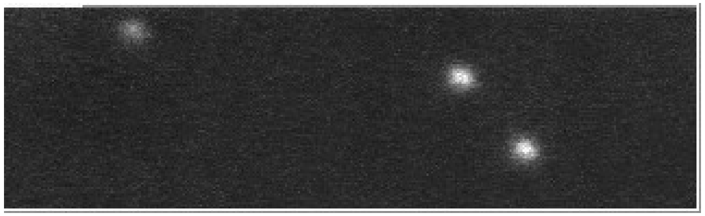
$$P = 0.033\ \mathrm{s},$$

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

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

Время жизни $\tau = P/(2\mathrm{d}P/\mathrm{d}t) \sim 1000$ years

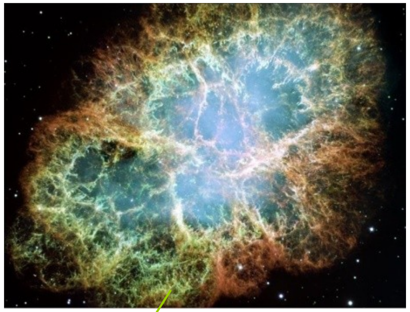
Оптические излучение



1054AD

Момент истины

Пульсар в Крабовидной туманности



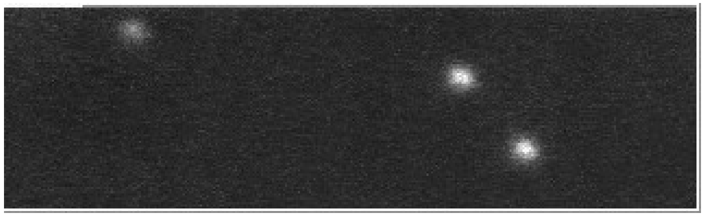
$$P = 0.034\ \mathrm{s},$$

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

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

Время жизни $\tau = P/(2\mathrm{d}P/\mathrm{d}t) \sim 1000$ years

Оптические излучение



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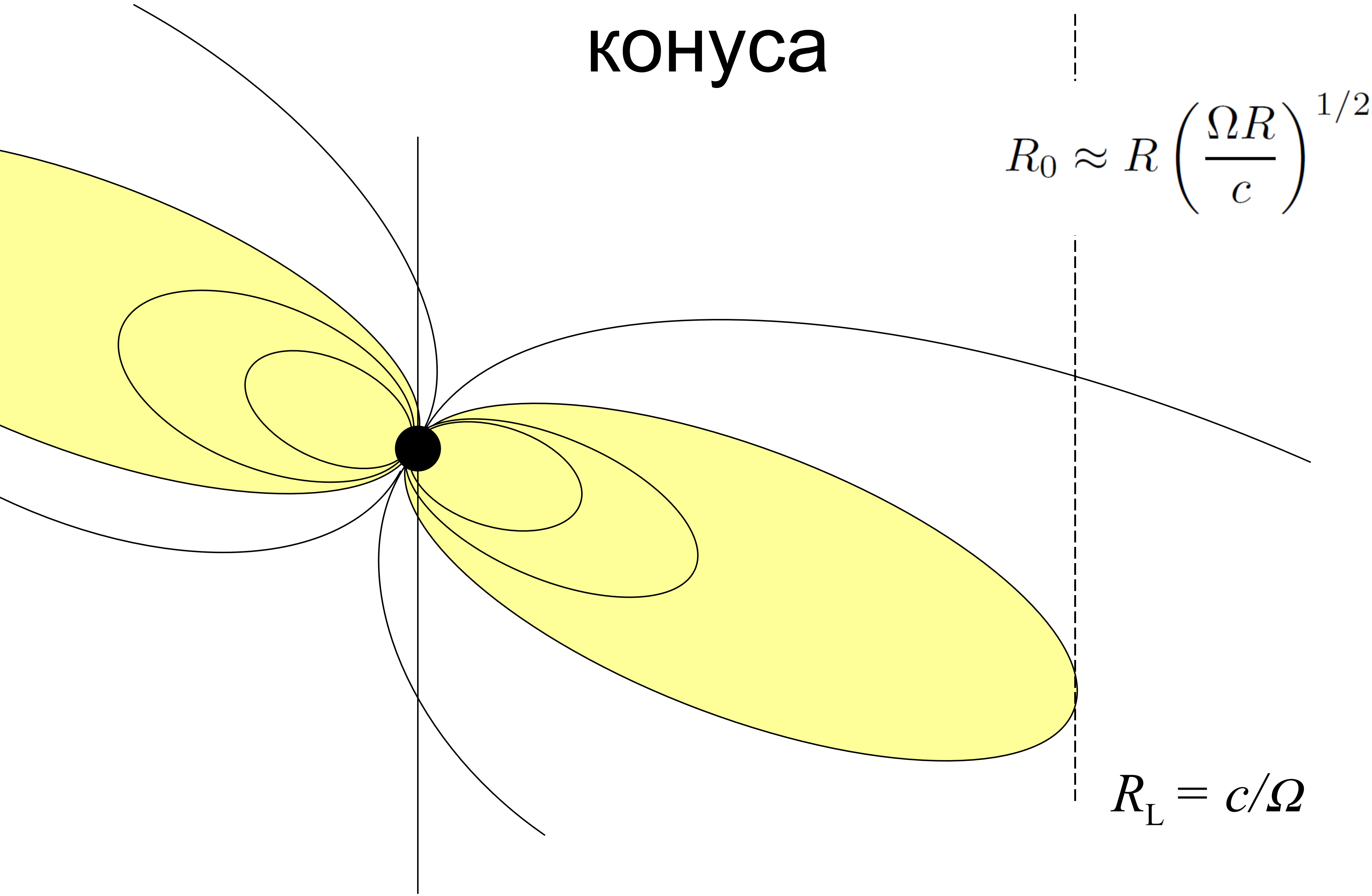
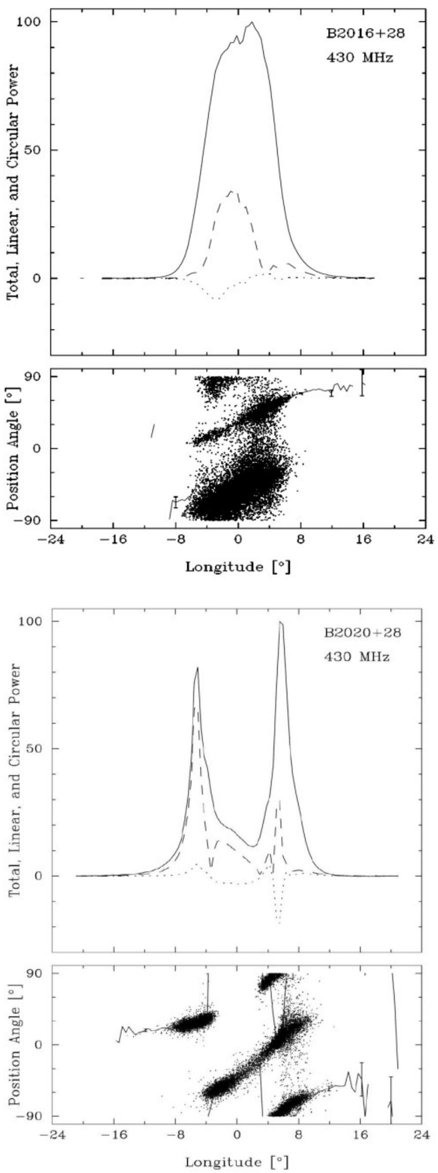
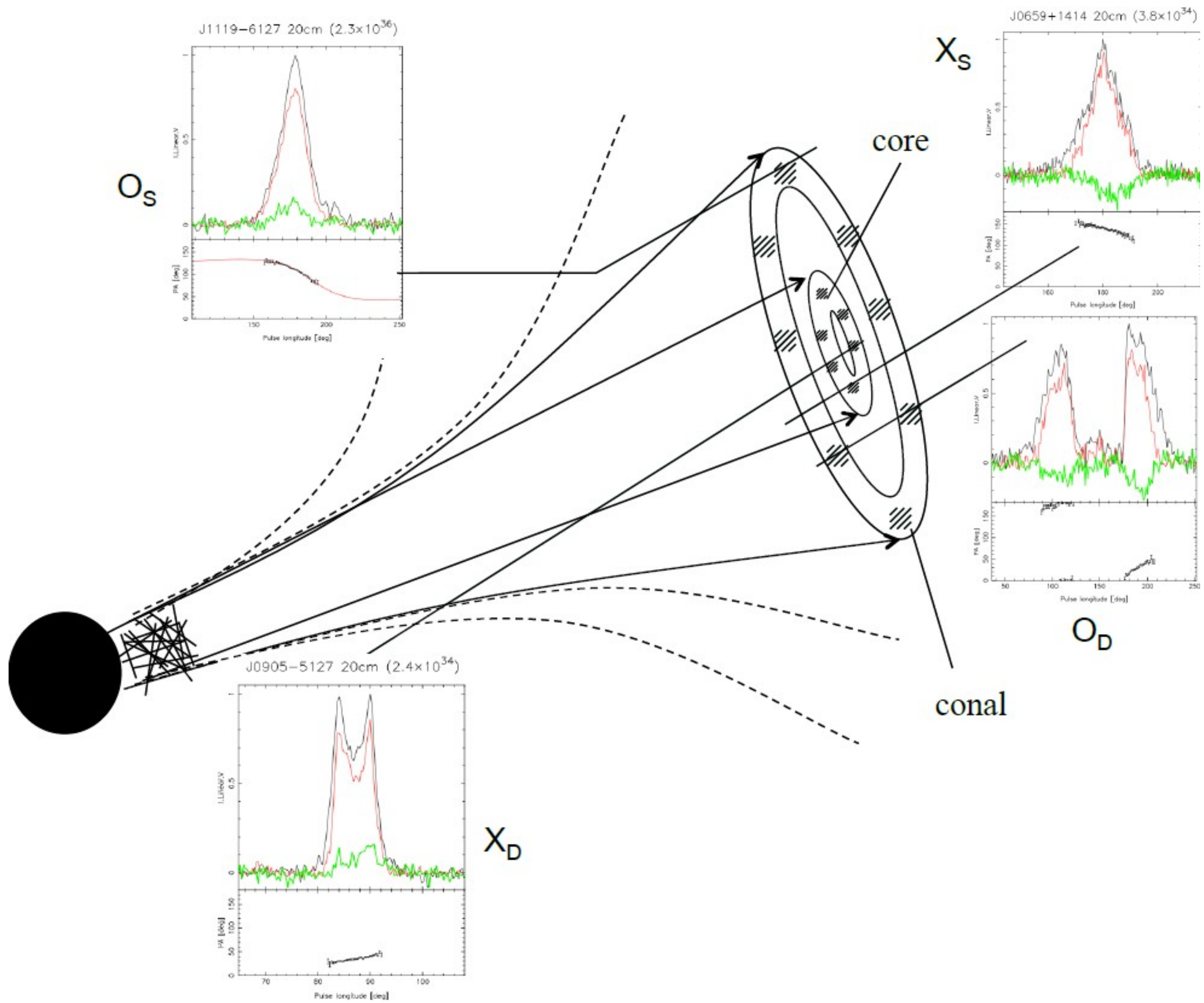
Рождение частиц, модель полого конуса



T.Hankins & J.Rankin (2008) VB & A.Philippov (2012)





Бессиловое приближение

Можно пренебречь энергией частиц

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

Mestel equation (1973)

$$\boxed{\nabla \times \tilde{\mathbf{B}} = \psi \mathbf{B}}$$

$$\tilde{\mathbf{B}} = \left\{B_r\left(1 - \frac{\Omega^2 r^2}{c^2}\right),\ B_\theta,\ B_z\left(1 - \frac{\Omega^2 r^2}{c^2}\right)\right\}$$

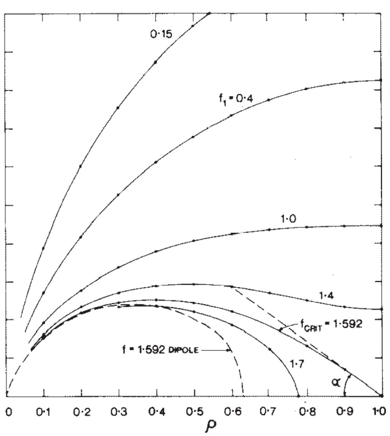
Pulsar equation

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

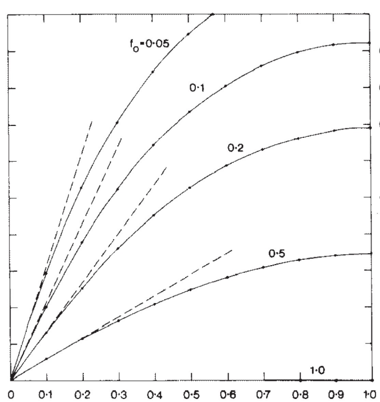
(Michel 1973, Mestel 1993, Scharlemann & Wagoner 1973,
Okamoto 1974, Mestel & Wang 1979)

Первые решения

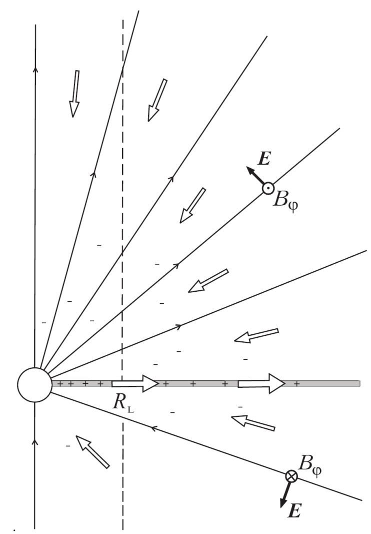
$$-\left(1-\frac{\Omega_{\rm F}^2\varpi^2}{c^2}\right)\nabla^2\Psi+\frac{2}{\varpi}\frac{\partial\Psi}{\partial\varpi}-\frac{16\pi^2}{c^2}I\frac{{\rm d}I}{{\rm d}\Psi}+\frac{\varpi^2}{c^2}\left(\nabla\Psi\right)^2\Omega_{\rm F}\frac{{\rm d}\Omega_{\rm F}}{{\rm d}\Psi}=0$$



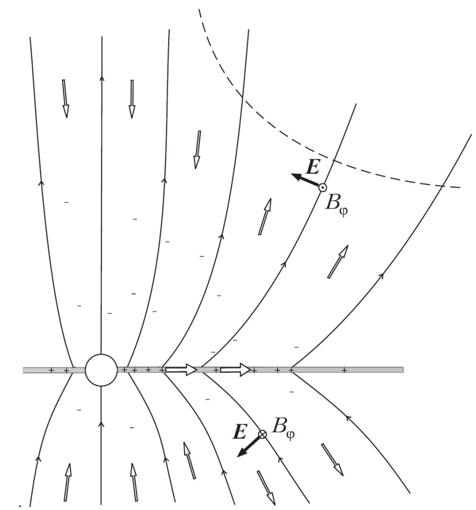
F. Michel (1973)



F. Michel (1973)

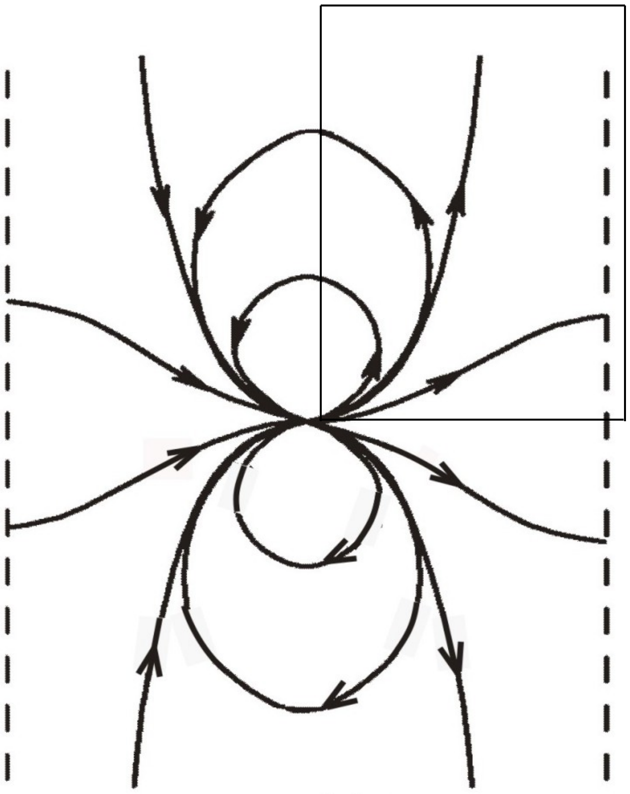


F. Michel (1973)

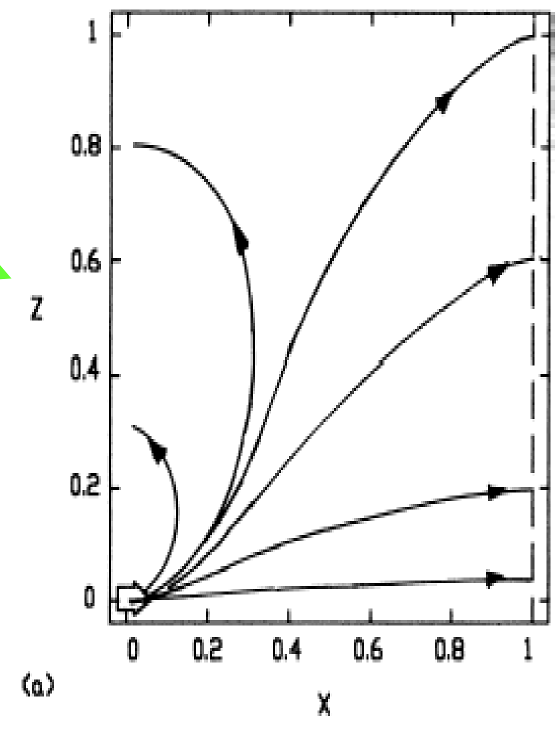


R.Blandford (1976)

Ортогональный случай



$\chi = 90^\circ$

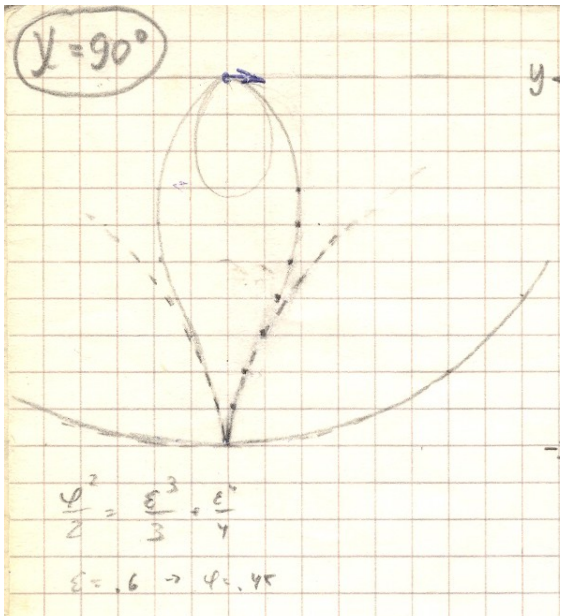


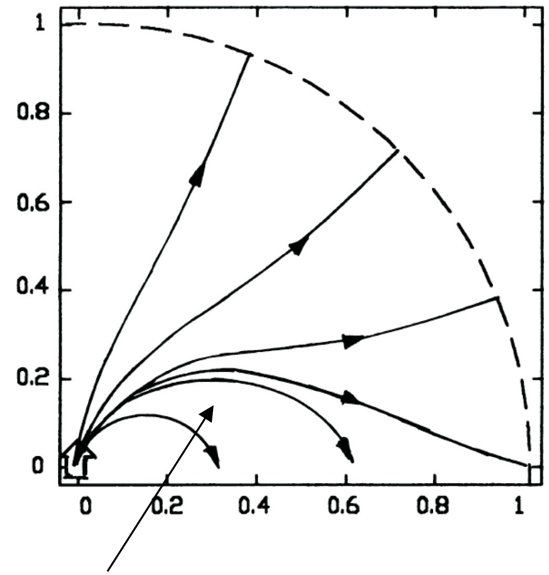
VB, A.V.Gurevich, Ya.N.Istomin, Sov. Phys. JETP, **58**, 235 (1983)

L.Mestel, P.Panagi, S.Shibata, MNRAS, **309**, 388 (1999)

Ортогональный случай

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



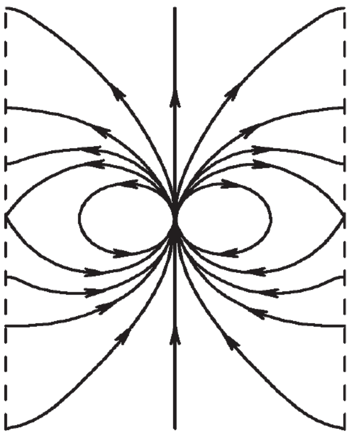


Equatorial plane

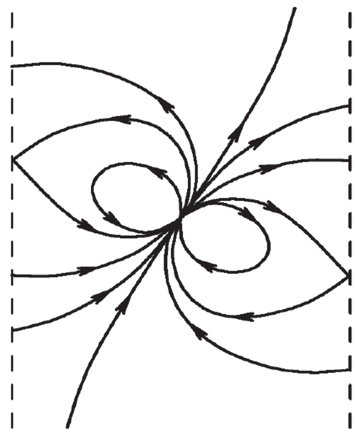
НЕТ ПОТЕРЬ!!

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

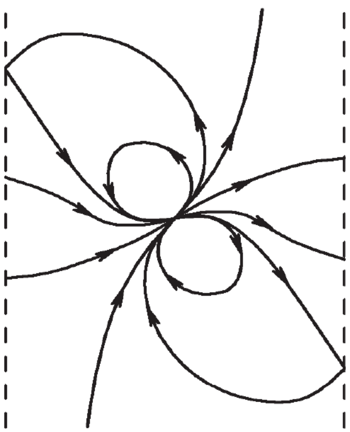
Наклонный ротатор



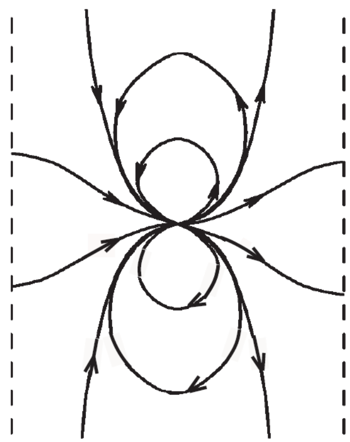
$\chi = 0^\circ$



$\chi = 30^\circ$

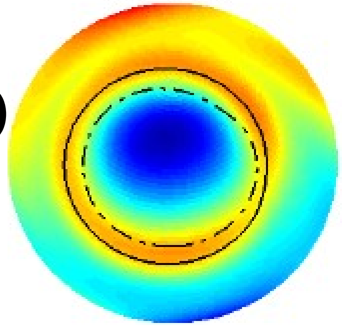


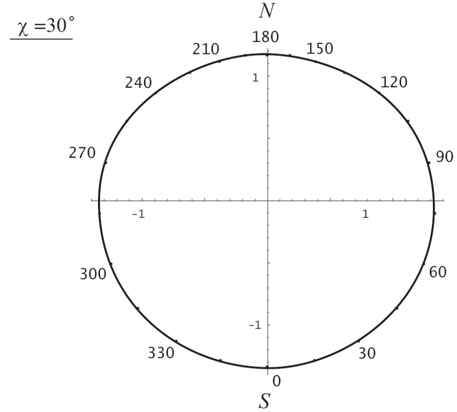
$\chi = 60^\circ$

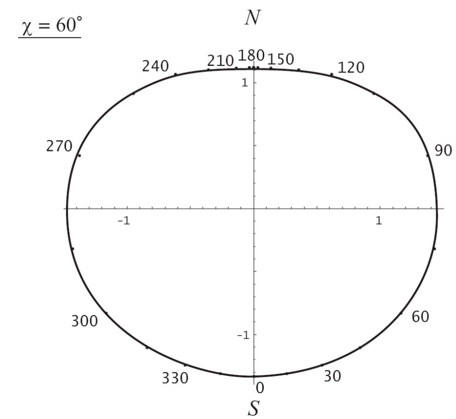


$\chi = 90^\circ$

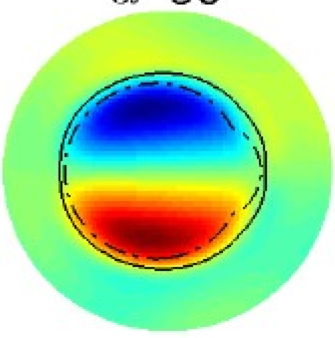
α=30°

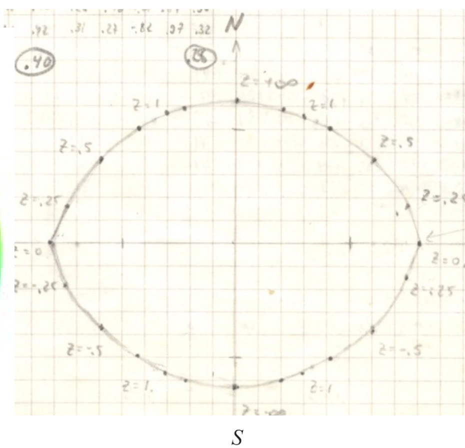






α=90°





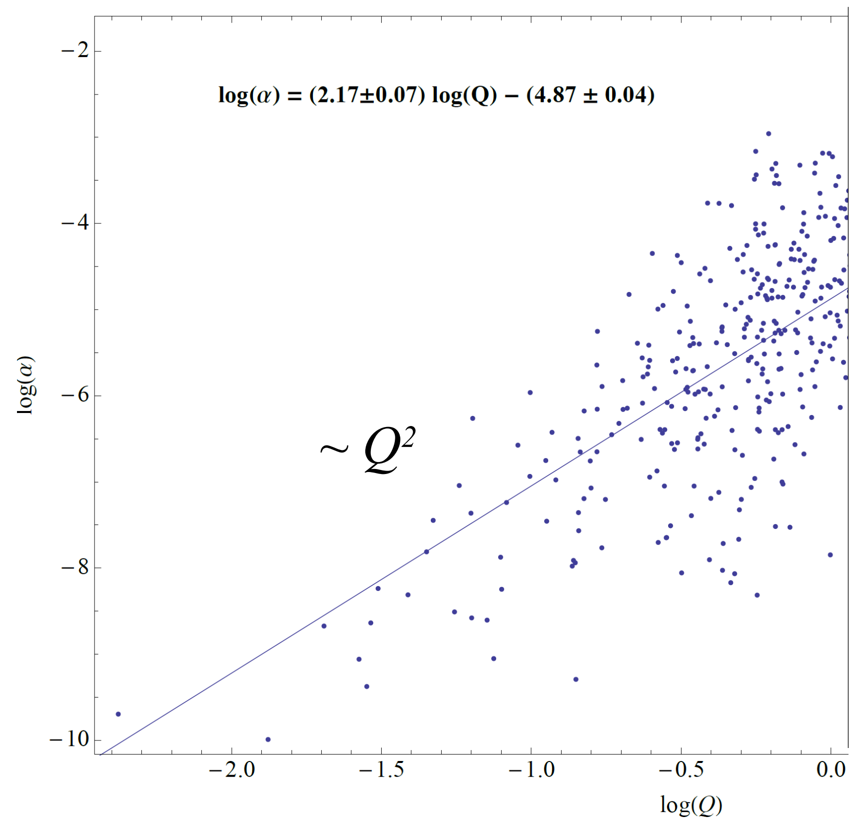
VB, A.V.Gurevich, Ya.N.Istomin (1983)

Замечание 1 (доля радиоизлучения)

$$Q = 2\,P^{11/10}\,\dot{P}_{-15}^{-4/10} \quad \text{(RS)}$$

- $H/R_0 \sim Q$ for $Q < 1$
- $W_{\rm part}/W_{\rm tot} \sim Q^2$

$$\alpha = L_{\rm rad}/W_{\rm tot}$$

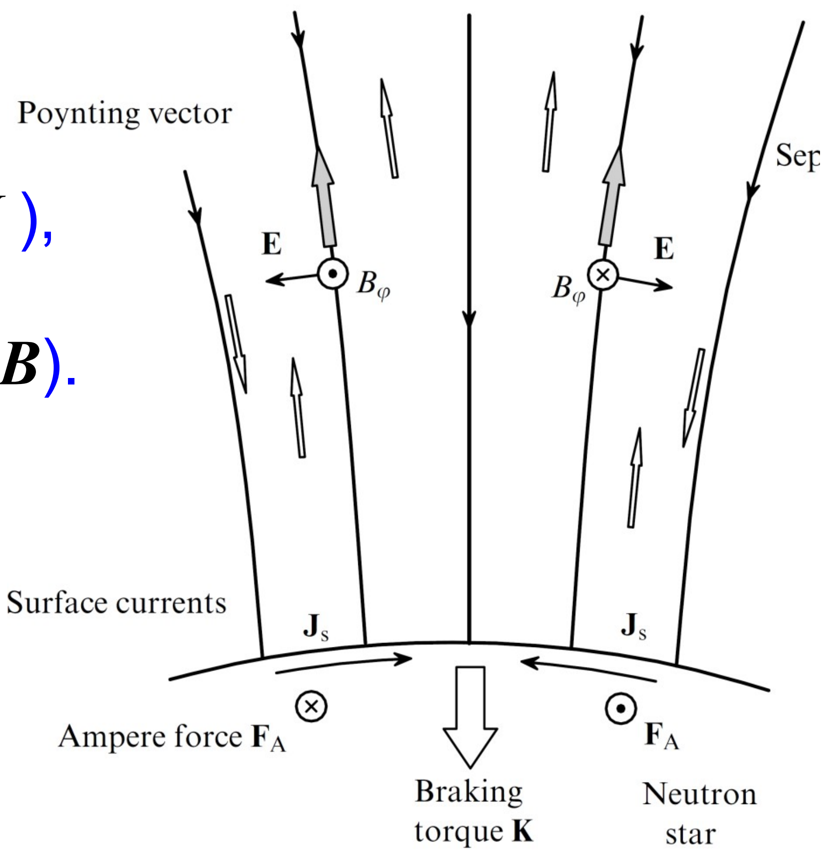


Токовые потери

For current loss mechanism is necessary to have

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

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



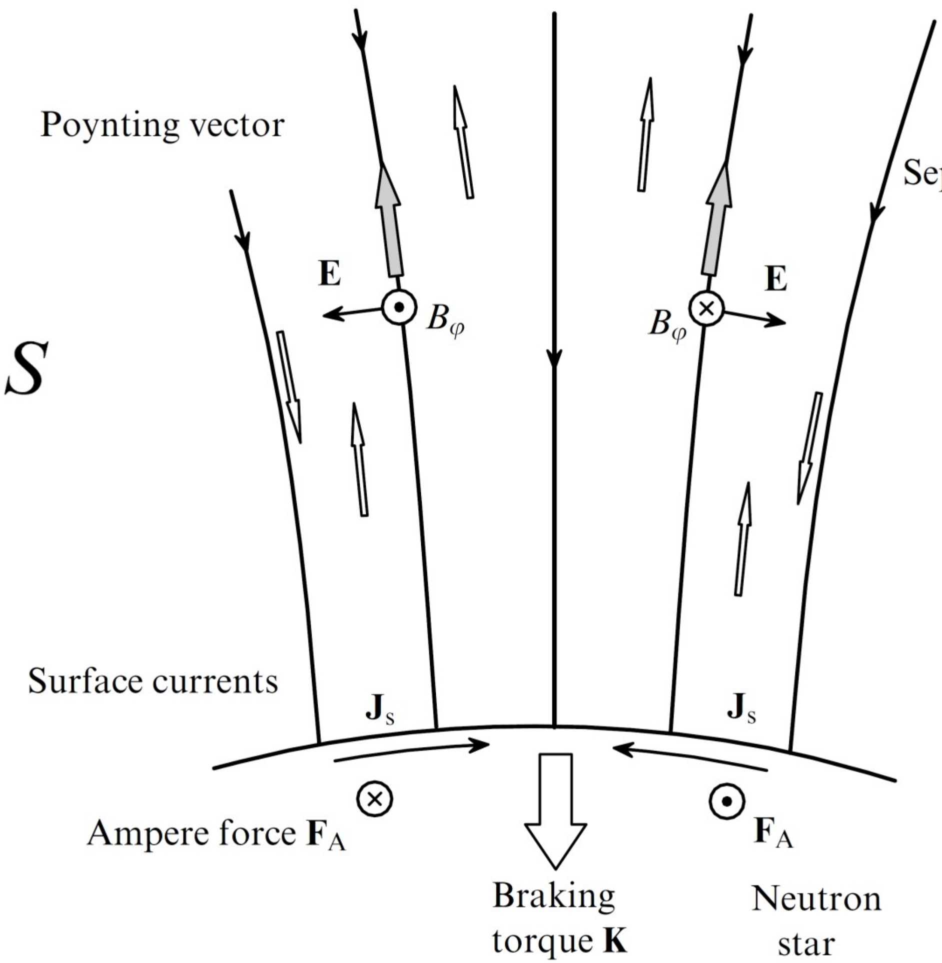
Токовые потери

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

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

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

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



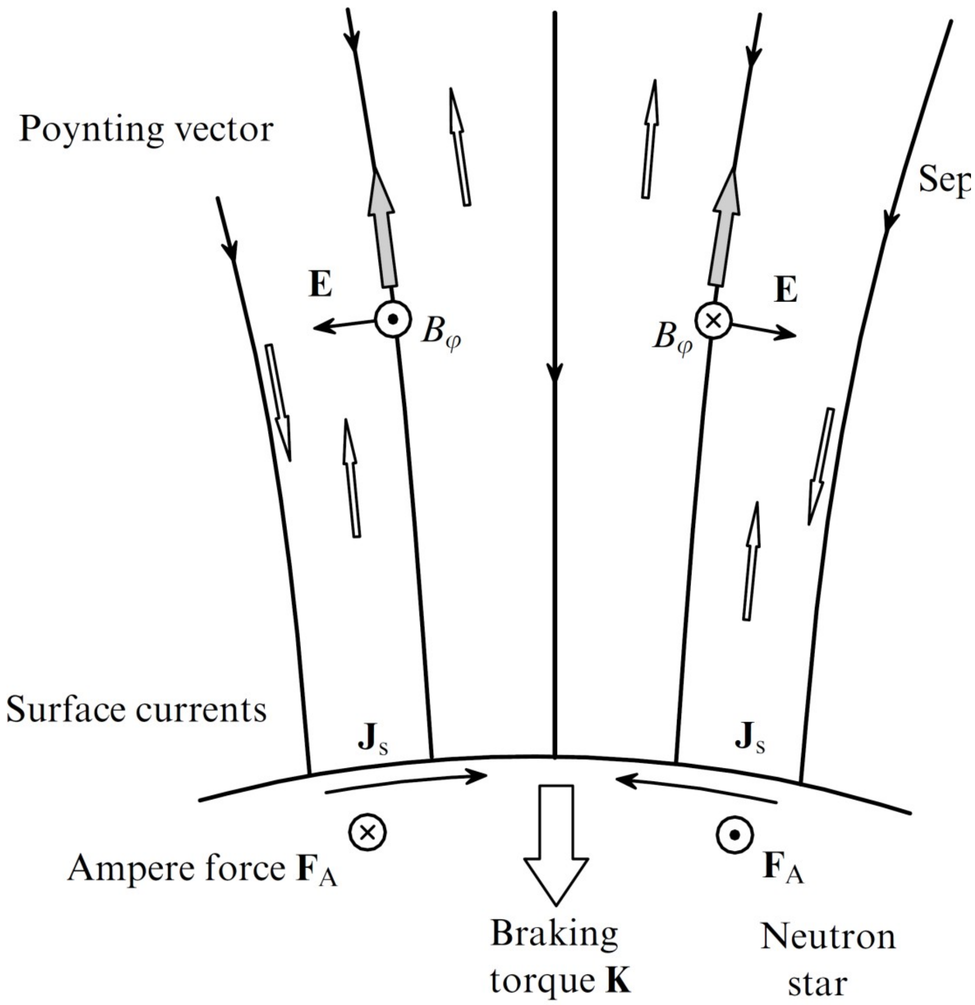
Токовые потери

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

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

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

GJ

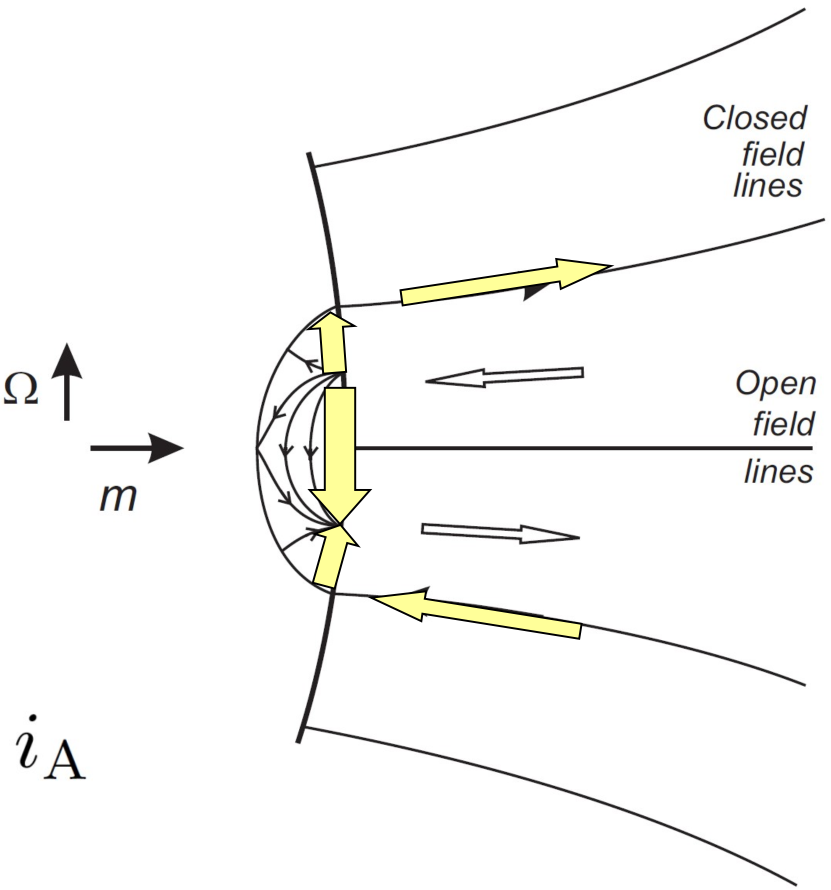


Ортогональный ротатор

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

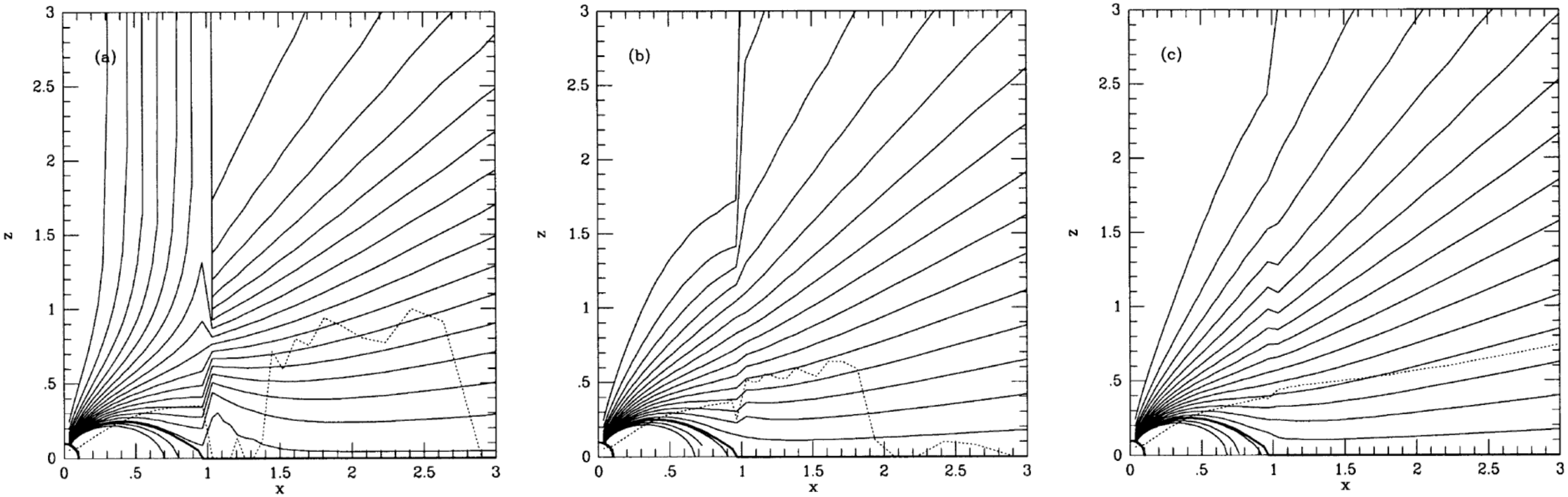
$$j_{\mathrm{GJ}} \approx \frac{\Omega B}{2\pi} \cos\theta$$

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



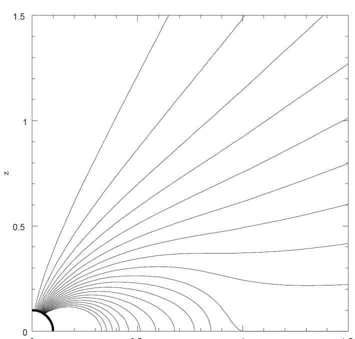
$$W_{\mathrm{tot}} = c_{\perp} \frac{B_0^2 \Omega^4 R^6}{c^3} \left(\frac{\Omega R}{c}\right) i_{\mathrm{A}}$$

$i_{\mathrm{A}} = j_{\parallel} / \rho_{\mathrm{GJ}} c$

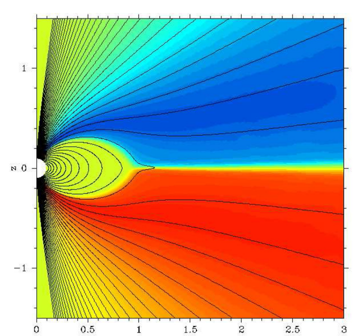


I.Contopoulos, D.Kazanas & Ch.Fendt, ApJ, **511**, 351 (1999)

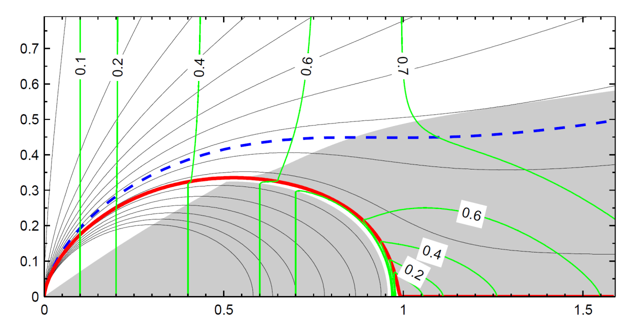
$$-\left(1-\frac{\Omega_{\mathrm{F}}^2\varpi^2}{c^2}\right)\nabla^2\Psi+\frac{2}{\varpi}\frac{\partial\Psi}{\partial\varpi}-\frac{16\pi^2}{c^2}I\frac{\mathrm{d}I}{\mathrm{d}\Psi}+\frac{\varpi^2}{c^2}\left(\nabla\Psi\right)^2\Omega_{\mathrm{F}}\frac{\mathrm{d}\Omega_{\mathrm{F}}}{\mathrm{d}\Psi}=0$$



A.Gruzinov (2005)

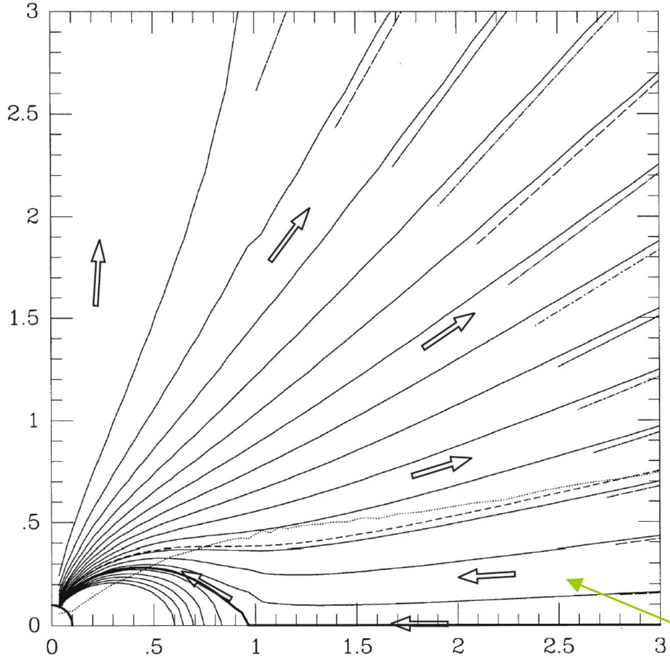


S.Komissarov (2005)

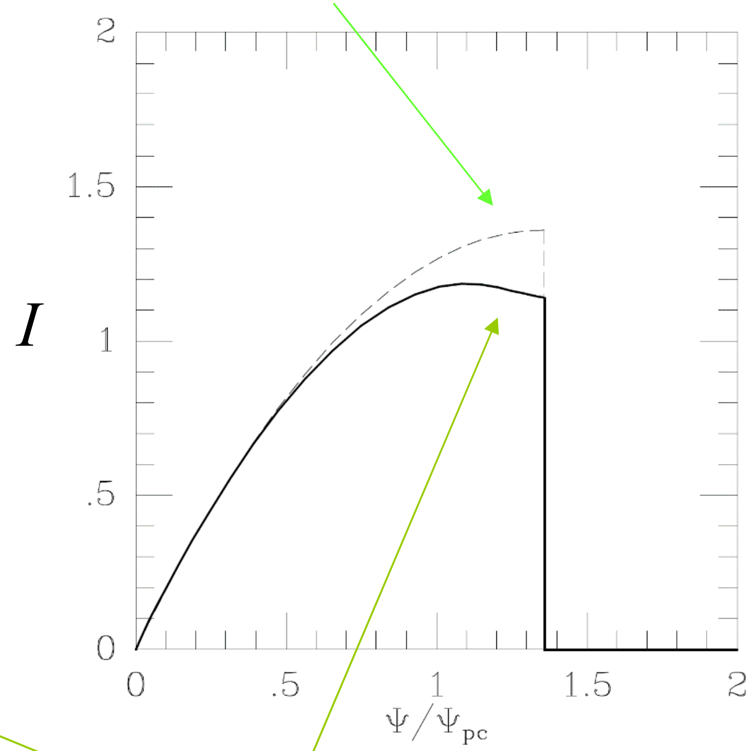


A.Timokhin (2005)

Проблема



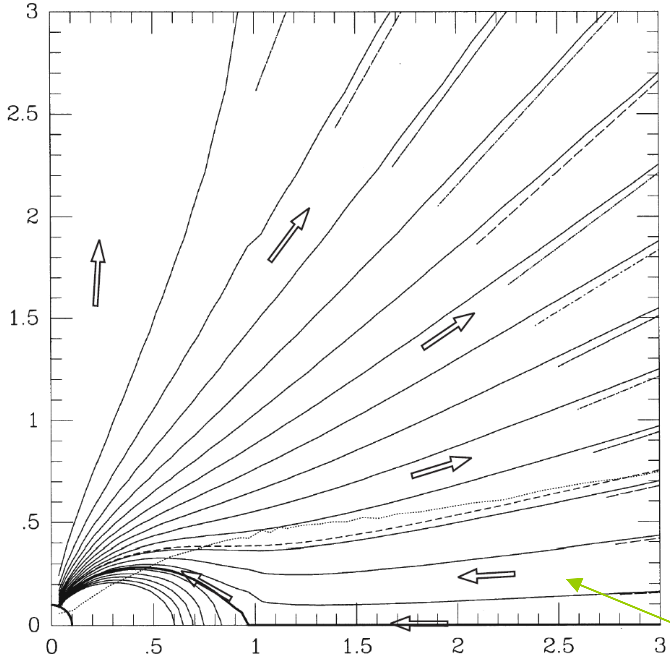
Michel, 1973



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

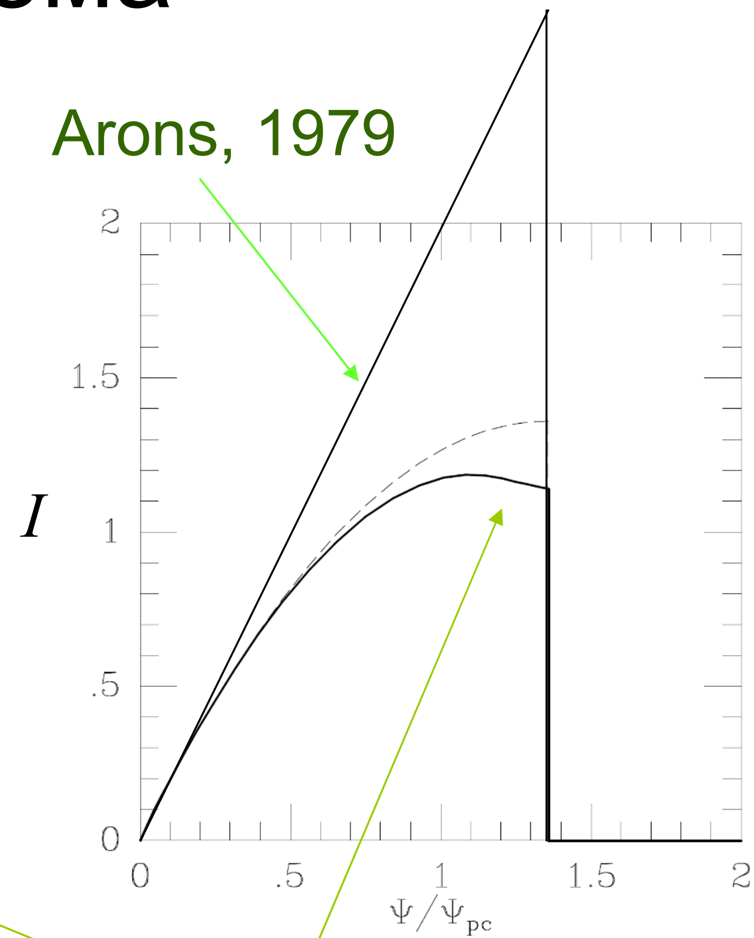
Обратный объемный ток

Проблема



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

Arons, 1979

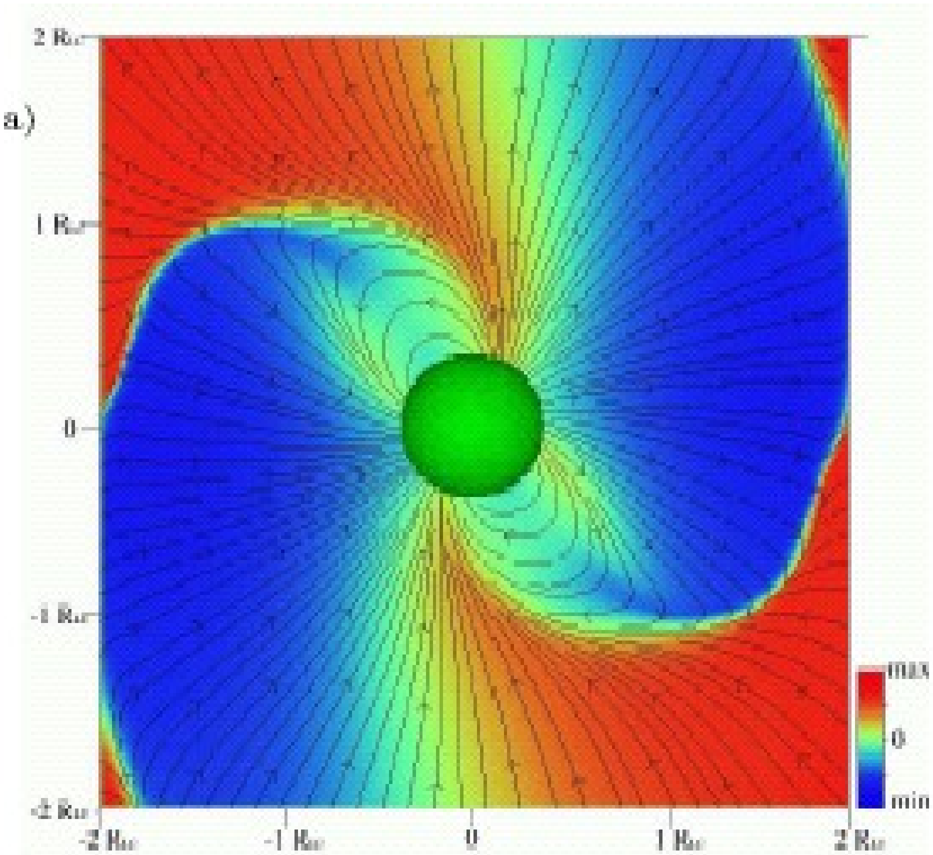


Обратный объемный ток

Inclined rotator

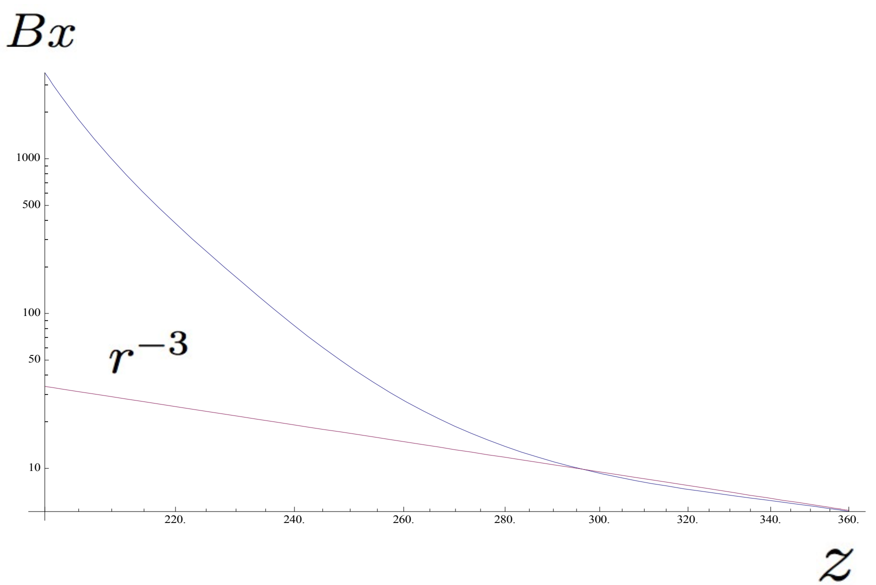
A.Spitkovsky, ApJ Lett., **648**, L51 (2006)

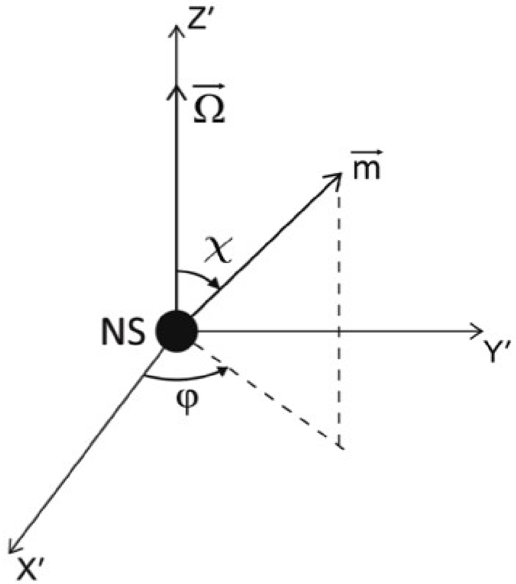
$$W_{\rm tot}^{\rm (MHD)} \approx \frac{1}{4}\frac{B_0^2\Omega^4R^6}{c^2}(1+\sin^2\chi)$$



Решение Спитковского, $\chi = 60^{o}$

Магнито-дипольных потерь нет

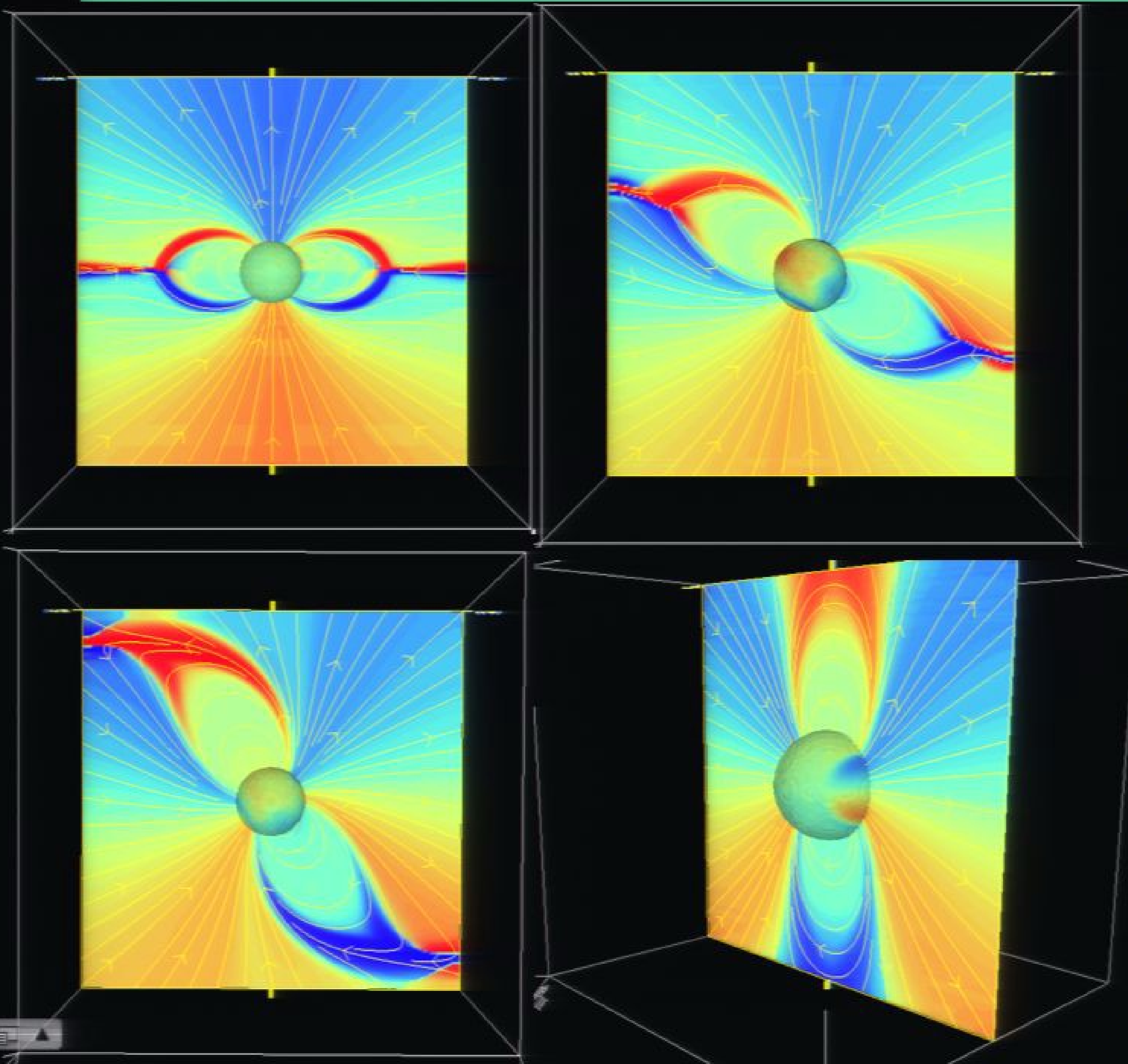




In vacuum $B_x = \frac{\ddot{d}}{cr}$

VB, YA.N.Istomin, A.A.Philippov, Phys. Uspekhi, **56**, 164 (2013)

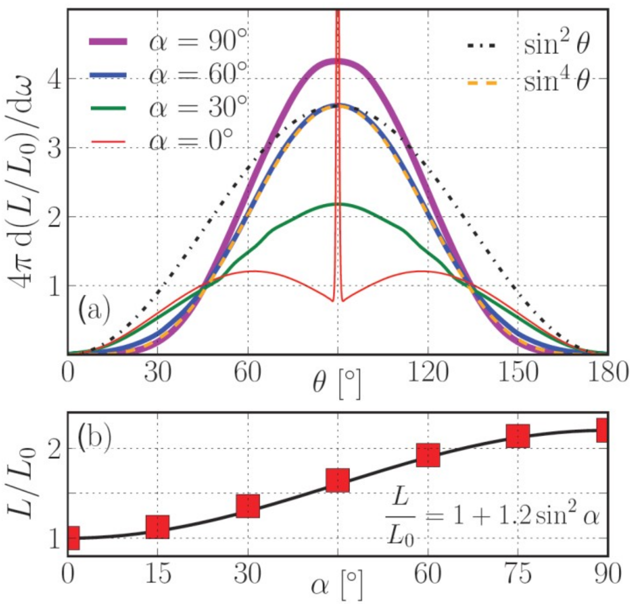
Magnetospheric currents

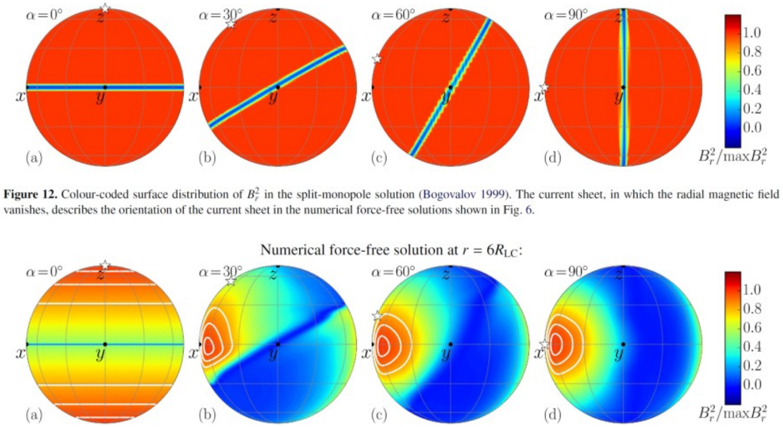


Oppositely flowing currents can occupy the same open flux tube. Does this have any obervational implications?

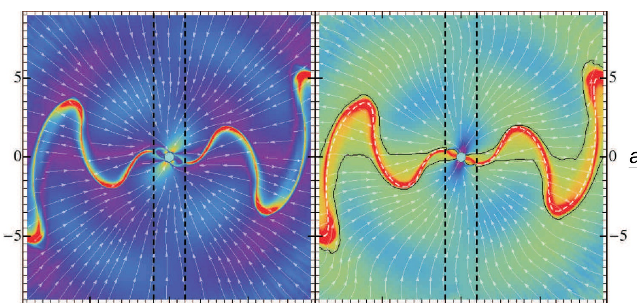
There is always a null-current field line in the open zone.

Наклонный ротатор - численно





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



I.Contopoulos et al

$$\langle B_r \rangle \sim \sin\theta$$
$$\langle E \rangle, \langle B_\varphi \rangle \sim \sin^2\theta$$

$$W_{\rm tot}(\theta) = \sin^2\theta B_r^2(\theta)$$

Эволюция – токовые потери?

$$I_{\rm r}\,\dot{\Omega} = K_{||}\cos\chi + K_{\perp}\sin\chi,$$

$$I_{\rm r}\Omega\,\dot{\chi} = K_{\perp}\cos\chi - K_{||}\sin\chi,$$

$$K_{||} = -c_{||}\frac{B_0^2\Omega^3R^6}{c^3}i_{\rm s},$$

$$K_{\perp} = -c_{\perp}\frac{B_0^2\Omega^3R^6}{c^3}\left(\frac{\Omega R}{c}\right)i_{\rm a}.$$

$$K_{\perp}^{A} \approx \left(\frac{\Omega R}{c}\right)K_{||}^{A}$$

$$i_{\rm s} \approx i_{\rm a} \approx 1$$

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

Эволюция – токовые потери?

$$
\begin{aligned}
I_{\rm r}\,\dot{\Omega} &= K_{\parallel}\cos\chi + K_{\perp}\sin\chi,\\
I_{\rm r}\Omega\,\dot{\chi} &= K_{\perp}\cos\chi - K_{\parallel}\sin\chi,
\end{aligned}
$$

$$
\begin{aligned}
I_{\rm r}\dot{\Omega} &= K_{\parallel}^{A} + [K_{\perp}^{A} - K_{\parallel}^{A}]\sin^2\chi,\\
I_{\rm r}\Omega\dot{\chi} &= [K_{\perp}^{A} - K_{\parallel}^{A}]\sin\chi\cos\chi.
\end{aligned}
$$

$$
\begin{aligned}
K_{\parallel} &= -c_{\parallel}\frac{B_0^2\Omega^3R^6}{c^3}i_{\rm s},\\
K_{\perp} &= -c_{\perp}\frac{B_0^2\Omega^3R^6}{c^3}\left(\frac{\Omega R}{c}\right)i_{\rm a}.
\end{aligned}
$$

$$
\begin{aligned}
i_{\rm s} &= i_{\rm s}^{A}\cos\chi,\\
i_{\rm a} &= i_{\rm a}^{A}\sin\chi.
\end{aligned}
$$

$$K_{\perp}^{A} \approx \left(\frac{\Omega R}{c}\right)K_{\parallel}^{A}$$

$$i_{\rm s} \approx i_{\rm a} \approx 1$$

$$i_{\rm A} \sim (\Omega R/c)^{-1}$$

BGI

Princeton (MHD)

Эволюция – токовые потери?

$$
\begin{aligned}
I_{\rm r}\,\dot{\Omega} &= K_{\parallel}\cos\chi + K_{\perp}\sin\chi, \\
I_{\rm r}\Omega\,\dot{\chi} &= K_{\perp}\cos\chi - K_{\parallel}\sin\chi,
\end{aligned}
$$

$$
\begin{aligned}
K_{\parallel} &= -c_{\parallel}\frac{B_0^2\Omega^3R^6}{c^3}i_{\rm s}, \\
K_{\perp} &= -c_{\perp}\frac{B_0^2\Omega^3R^6}{c^3}\left(\frac{\Omega R}{c}\right)i_{\rm a}.
\end{aligned}
$$

$$K_{\perp}^{A} \approx \left(\frac{\Omega R}{c}\right)K_{\parallel}^{A}$$

$$i_{\rm s} \approx i_{\rm a} \approx 1$$

BGI

$$
\begin{aligned}
I_{\rm r}\dot{\Omega} &= K_{\parallel}^{A} + [K_{\perp}^{A} - K_{\parallel}^{A}]\sin^2\chi, \\
I_{\rm r}\Omega\dot{\chi} &= [K_{\perp}^{A} - K_{\parallel}^{A}]\sin\chi\cos\chi.
\end{aligned}
$$

$$
\begin{aligned}
i_{\rm s} &= i_{\rm s}^{A}\cos\chi, \\
i_{\rm a} &= i_{\rm a}^{A}\sin\chi.
\end{aligned}
$$

?

$$i_{\rm A} \sim (\Omega R/c)^{-1}$$

Princeton (MHD)

Продольный ток

Дрейфовое приближение

$$\mathbf{j} = c\,\rho_{\rm e}\frac{[\mathbf{E}\times\mathbf{B}]}{B^2} + a\,\mathbf{B}$$

$$\boxed{\mathbf{j} = \rho_{\rm e}\,[\mathbf{\Omega}\times\mathbf{r}] + i_{\|}\,\mathbf{B}}$$

$$\boxed{\mathbf{j} = \frac{(\mathbf{B}\cdot\nabla\times\mathbf{B} - \mathbf{E}\cdot\nabla\times\mathbf{E})\mathbf{B} + (\nabla\cdot\mathbf{E})\mathbf{E}\times\mathbf{B}}{B^2}}$$

$$(\nabla i_{\|}\,\mathbf{B}) = 0$$

Mestel, BGI

Gruzinov

$$i_{\rm a} \sim \left(\frac{\Omega R}{c}\right)^{-1/2}$$

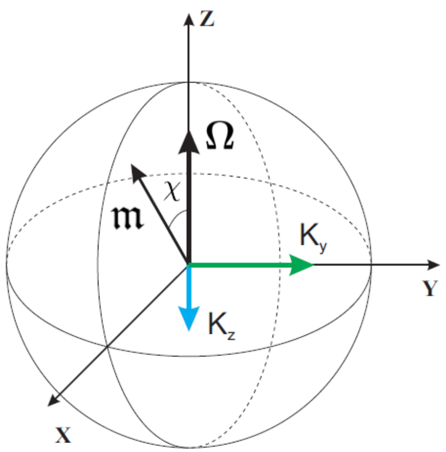
Не только!

$$\beta_{\mathrm{R}} = \frac{\mathbf{\Omega} \times \mathbf{r}}{c}$$

Энергетические потери

$$W_{\mathrm{tot}} = \frac{c}{4\pi} \int (\beta_{\mathrm{R}} \mathbf{B})(\mathbf{B} \mathrm{d} \mathbf{S})$$

Токовые (симм.)	$i_s \sim 1$	1	$\Omega^{3/2}$	$\Omega^{3/2}$	1	Ω	$= \Omega^4$
Токовые (ортог.)	$i_a \sim 1$	Ω	Ω	Ω^2	1	Ω	$= \Omega^5$
Вакуум (Л&Л) (2/3)		1	Ω	Ω^3	1	1	$= \Omega^4$



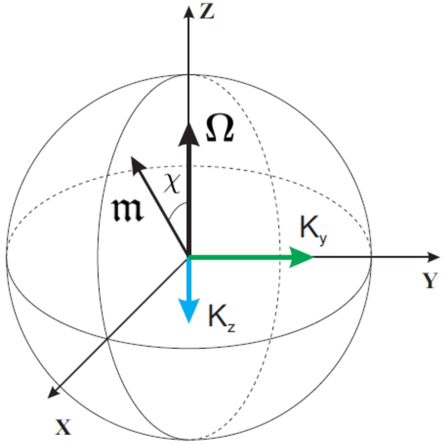
Не только!

$$\beta_{\rm R} = \frac{\mathbf{\Omega} \times \mathbf{r}}{c}$$

Энергетические потери

$$W_{\rm tot} = \frac{c}{4\pi} \int (\beta_{\rm R} \mathbf{B})(\mathbf{B} d\mathbf{S})$$

Токовые (симм.)	$i_{\rm s} \sim 1$	1	$\Omega^{3/2}$	$\Omega^{3/2}$	1	Ω	$= \Omega^4$
Токовые (ортог.)	$i_{\rm a} \sim 1$	Ω	Ω	Ω^2	1	Ω	$= \Omega^5$
Вакуум (Л&Л) (1/3)		1	Ω	1	Ω^3	1	$= \Omega^4$



$$\mathbf{B}^{(3)} = -\frac{2}{3} \frac{\mathfrak{m}}{R^3} \left(\frac{\Omega R}{c} \right)^3 \mathbf{e}_{y'}$$

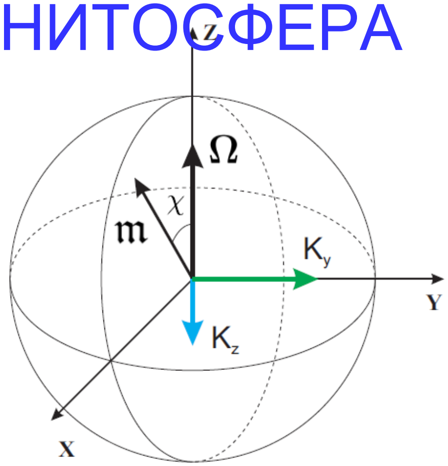
Не только!

$$\beta_{\mathrm{R}} = \frac{\boldsymbol{\Omega} \times \mathbf{r}}{c}$$

Энергетические потери

$$W_{\mathrm{tot}} = \frac{c}{4\pi} \int (\beta_{\mathrm{R}} \mathbf{B})(\mathbf{B} d\mathbf{S})$$

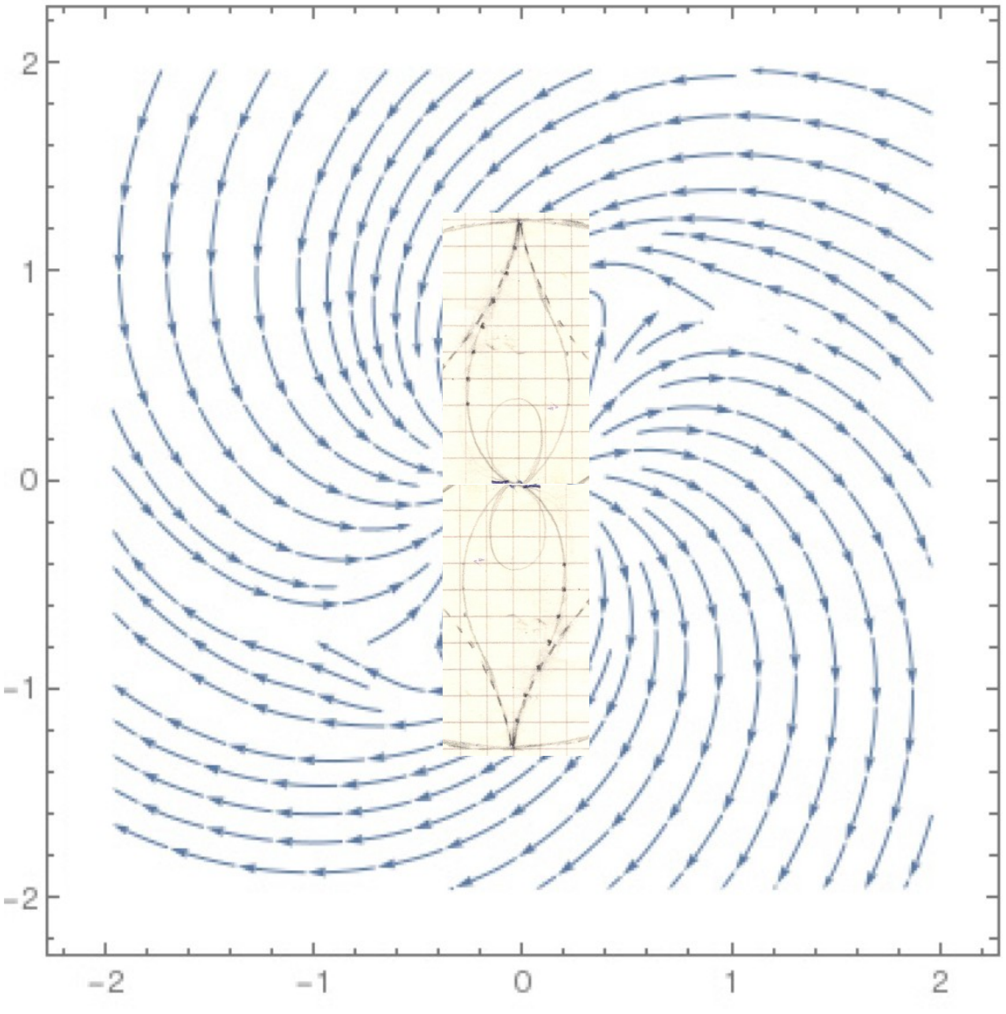
Токовые (симм.)	$i_s \sim 1$	1	$\Omega^{3/2}$	$\Omega^{3/2}$	1	Ω	$= \Omega^4$
Токовые (ортог.)	$i_a \sim 1$	Ω	Ω	Ω^2	1	Ω	$= \Omega^5$
Вакуум (Л&Л) (1/3)		1	Ω	1	Ω^3	1	$= \Omega^4$
МАГНИТОСФЕРА		1	Ω	1	Ω^3	1	$= \Omega^4$



$$\boxed{\mathbf{B}^{(3)} = -\frac{2}{3} \frac{\mathfrak{m}}{R^3} \left(\frac{\Omega R}{c} \right)^3 \mathbf{e}_{y'}}$$

Магнитосферные потери

За счет рассогласования



Магнитосферные потери

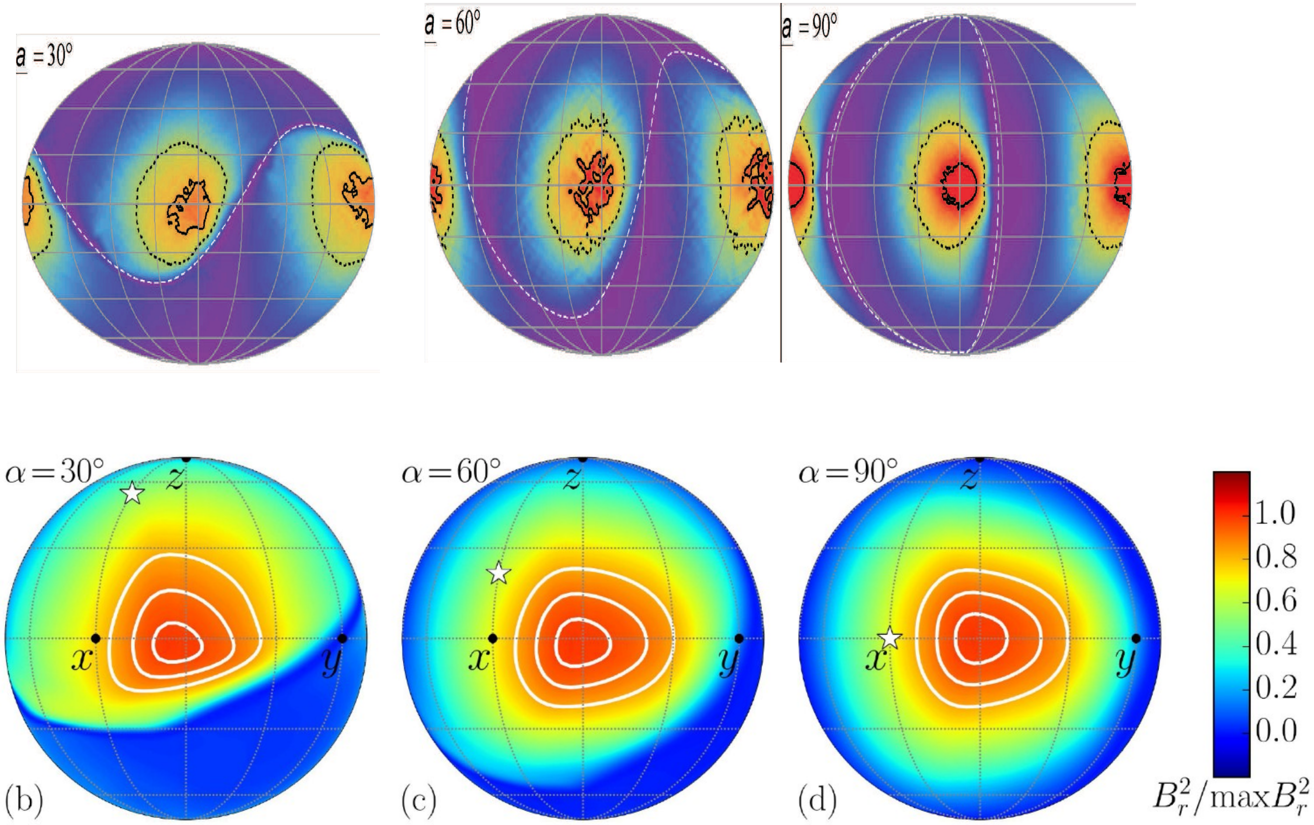
Момент сил

$$
\begin{aligned}
I_{\rm r}\dot{\Omega} &= K_{\parallel}^{A} + [K_{\perp}^{A} - K_{\parallel}^{A}]\sin^2\chi, \\
I_{\rm r}\Omega\dot{\chi} &= [K_{\perp}^{A} - K_{\parallel}^{A}]\sin\chi\cos\chi.
\end{aligned}
$$

$$
K_{\perp}^{\rm mag} = -A\,\frac{B_0^2\Omega^3 R^6}{c^3}\,i_{\rm a}
$$

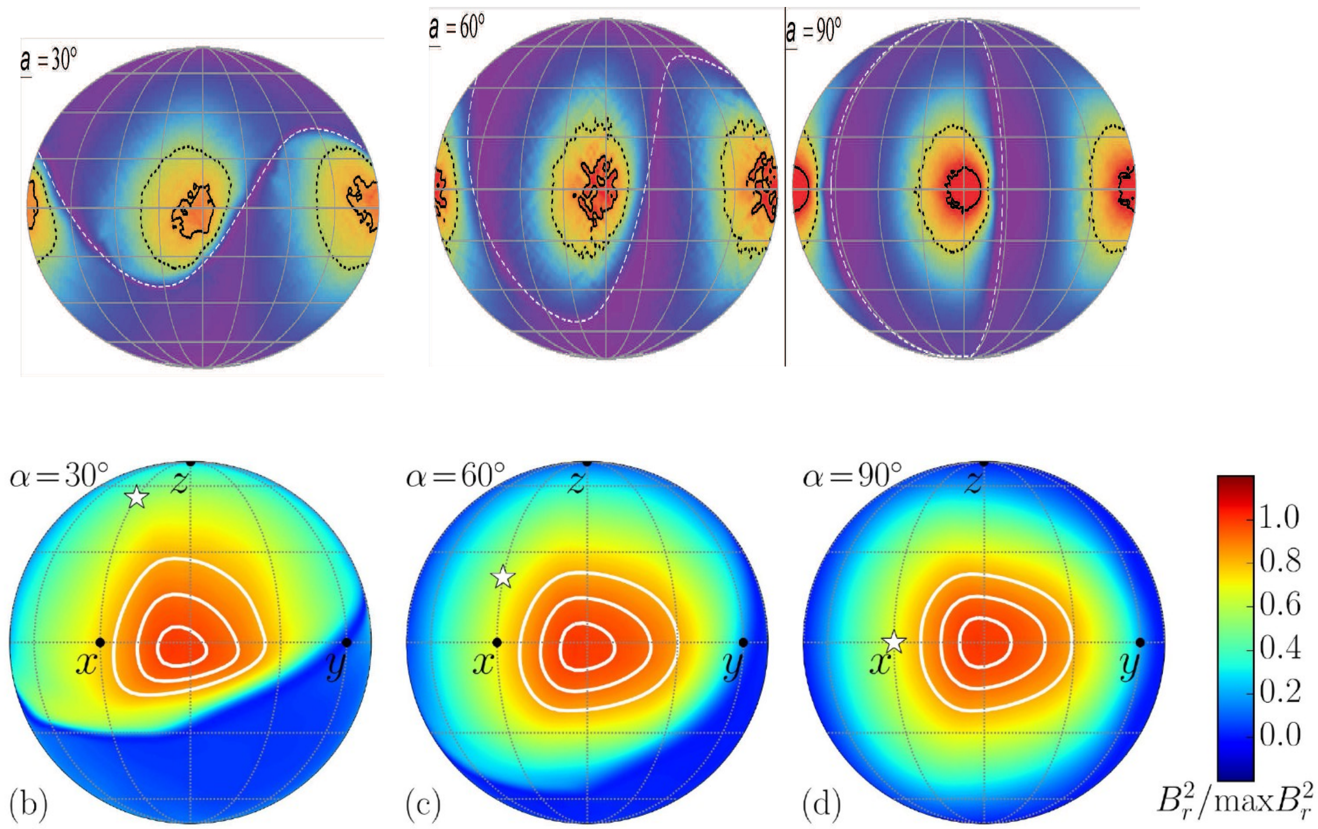
$$
\boxed{A \approx 2\left(\frac{\Omega R}{c}\right)^{1/2}}
$$

Так все-таки волна?



-

Так все-таки волна?



-

Да, но не магнито-дипольная!

Industrial revolution (2006 – 2012)

Main results

- There is universal inclined solution (with definite charge and current density!)
- No disagreement with the current losses model
- 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

Нет чистого эксперимента (braking index)

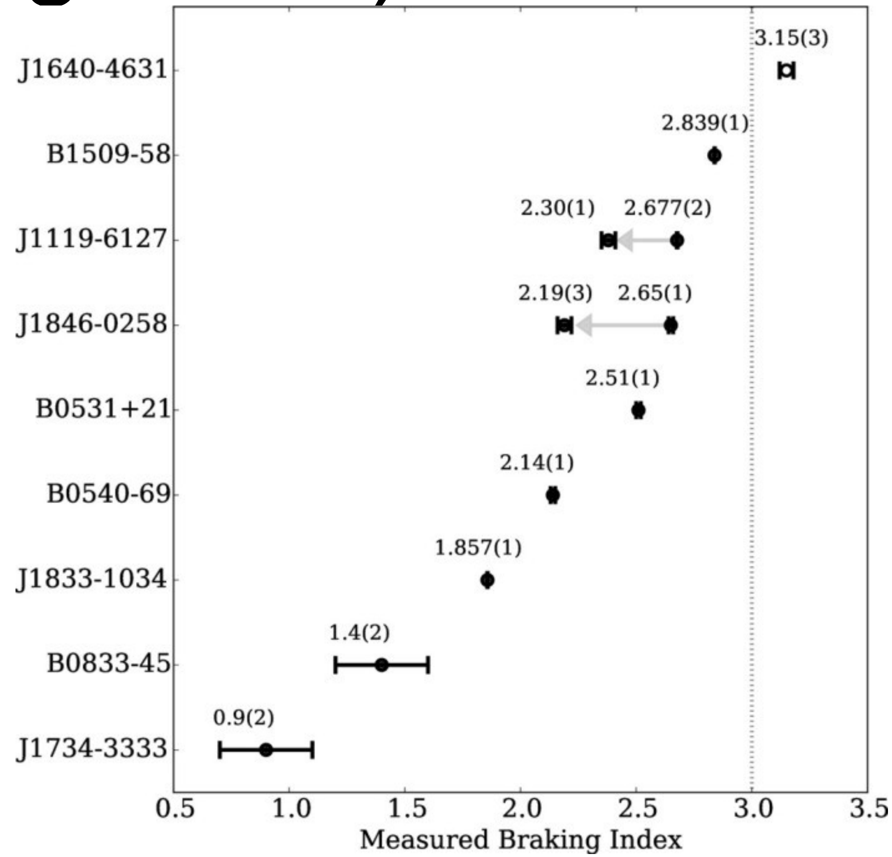
$$n_{\rm br} = \frac{\ddot{\Omega}\Omega}{\dot{\Omega}^2}$$

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

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

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

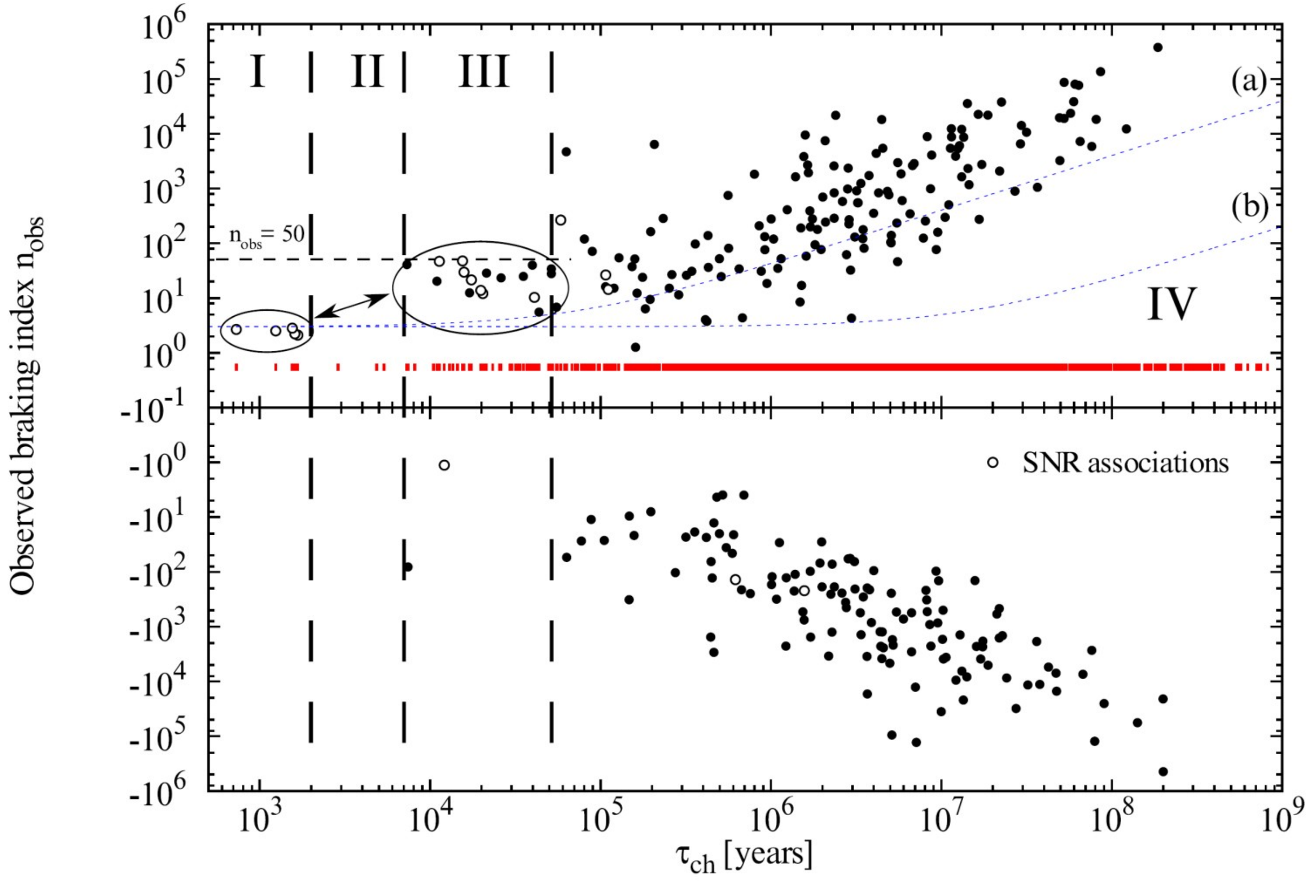
$$n_{\rm br} = 1{,}93 + 1{,}5\tan^2\chi$$



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

Нет чистого эксперимента
(braking index)

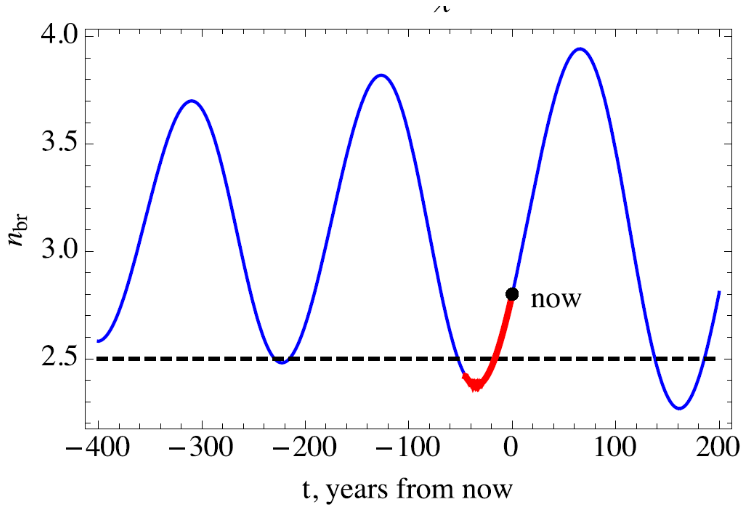
$$n_{\rm br} = \frac{\ddot{\Omega}\Omega}{\dot{\Omega}^2}$$

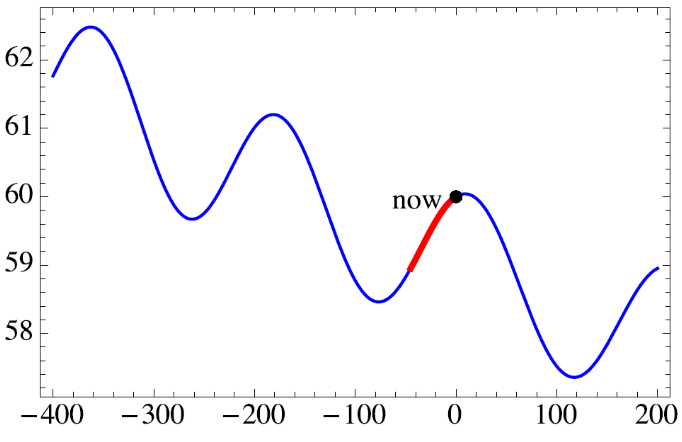


A.Biryukov, G.Beskin, S. Karpov, MNRAS, **420**, 103 (2012)

Нет чистого эксперимента (braking index)

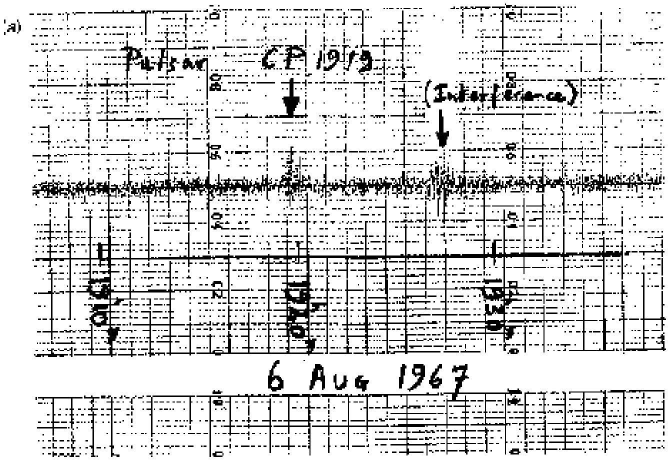
$$n_{\rm br} = \frac{\ddot{\Omega}\Omega}{\dot{\Omega}^2}$$

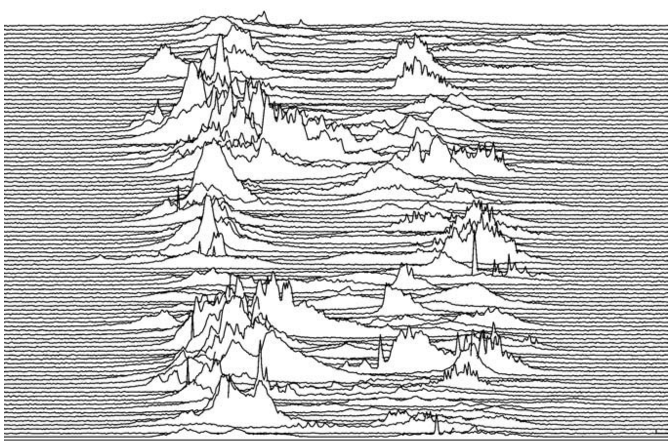


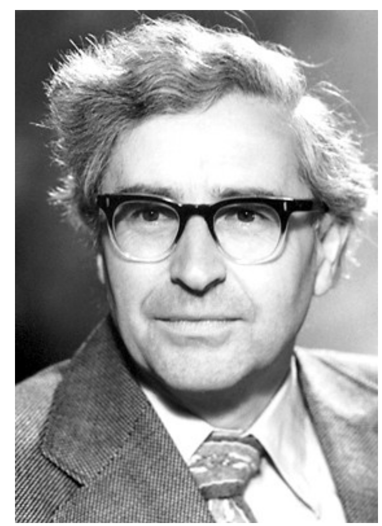


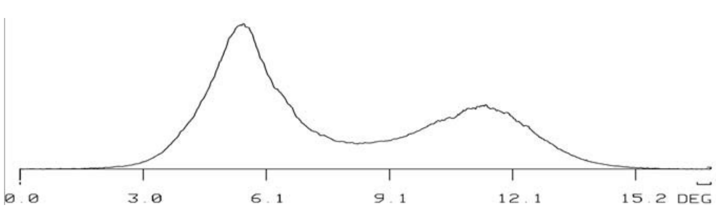
L.Arzamasskiy, A.Philippov, A.Tchekhovsky, MNRAS, **453**, 3540 (2015)

Jocelyn Bell, Antony Hewish, 1967









А воз и ныне там…

- (Механизм радиоизлучения)
- Углы наклона
  - Только острые?
  - Только тупые?
  - И те, и те?
- Ускорение в ветре

Благодарности

Спасибо!