Intrinsic Physical Conditions and Structure of Relativistic Jets in AGN

V.S. Beskin

P.N.Lebedev Physical Institute

Moscow Institute of Physics and Technology

with

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Guest star

Nadia Zakamska

Intrinsic Physical Conditions and Structure of Relativistic Jets in AGN

Guest star

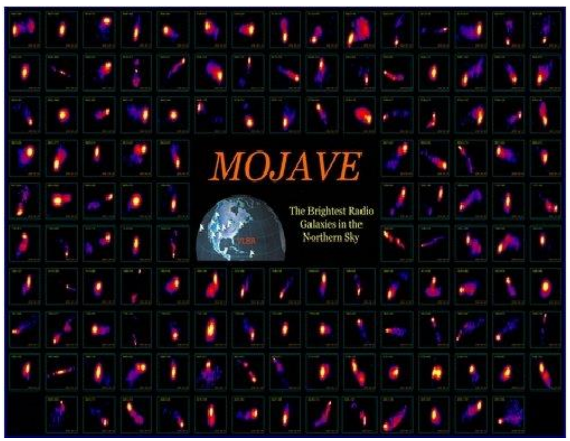
Nadia Zakamska

Plan

- Thanks
- AGN Jets – internal structure (observations)
- AGN Jets – internal structure (theory)
- Core shift and internal jet parameters
- Possible mechanisms of deceleration (poster)
- Thanks again

Internal structure – AGN

New possibilities

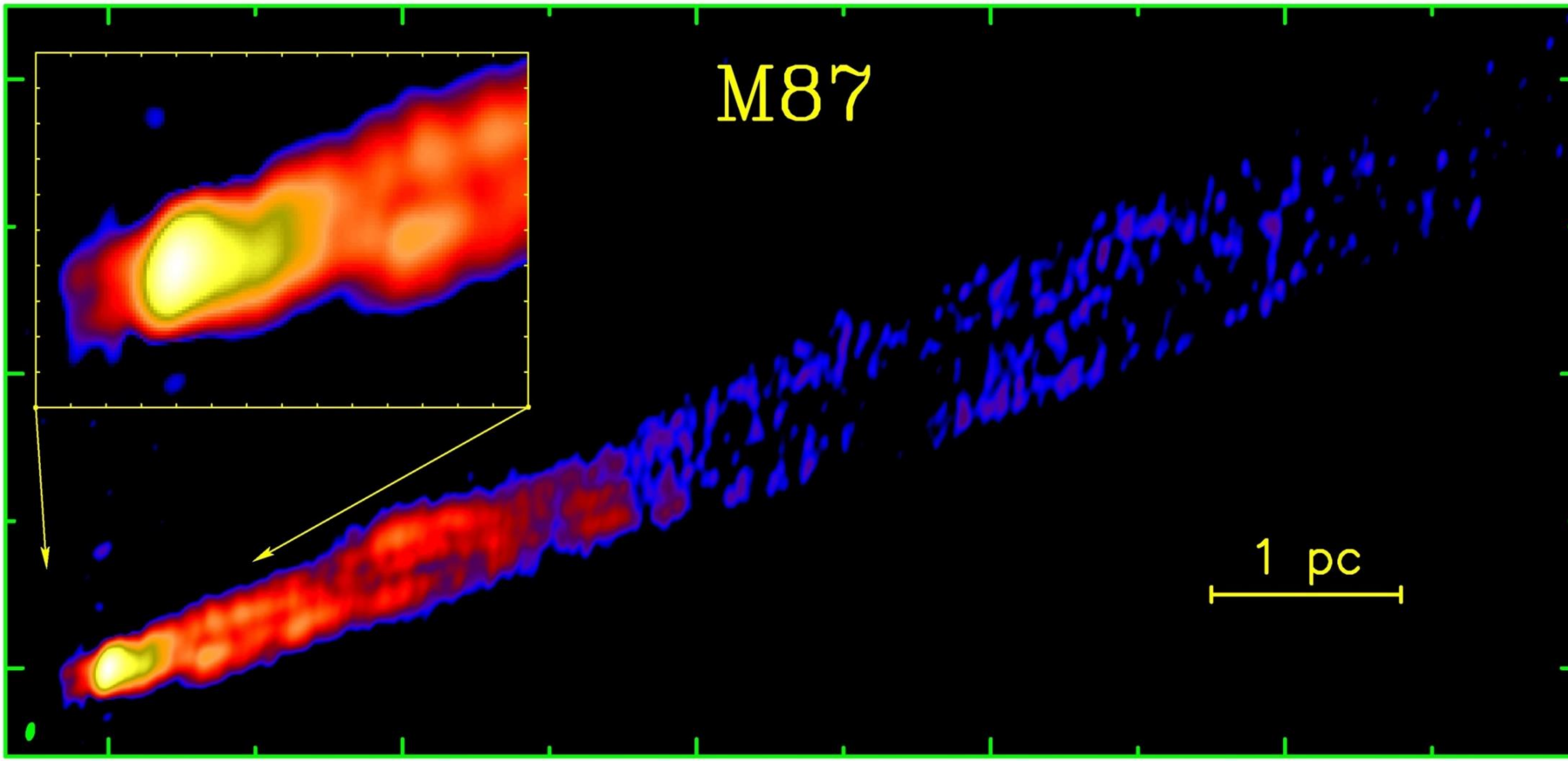


MOJAVE team (time)

Radioastron (base)

VLBA+VLA1, 15 GHz

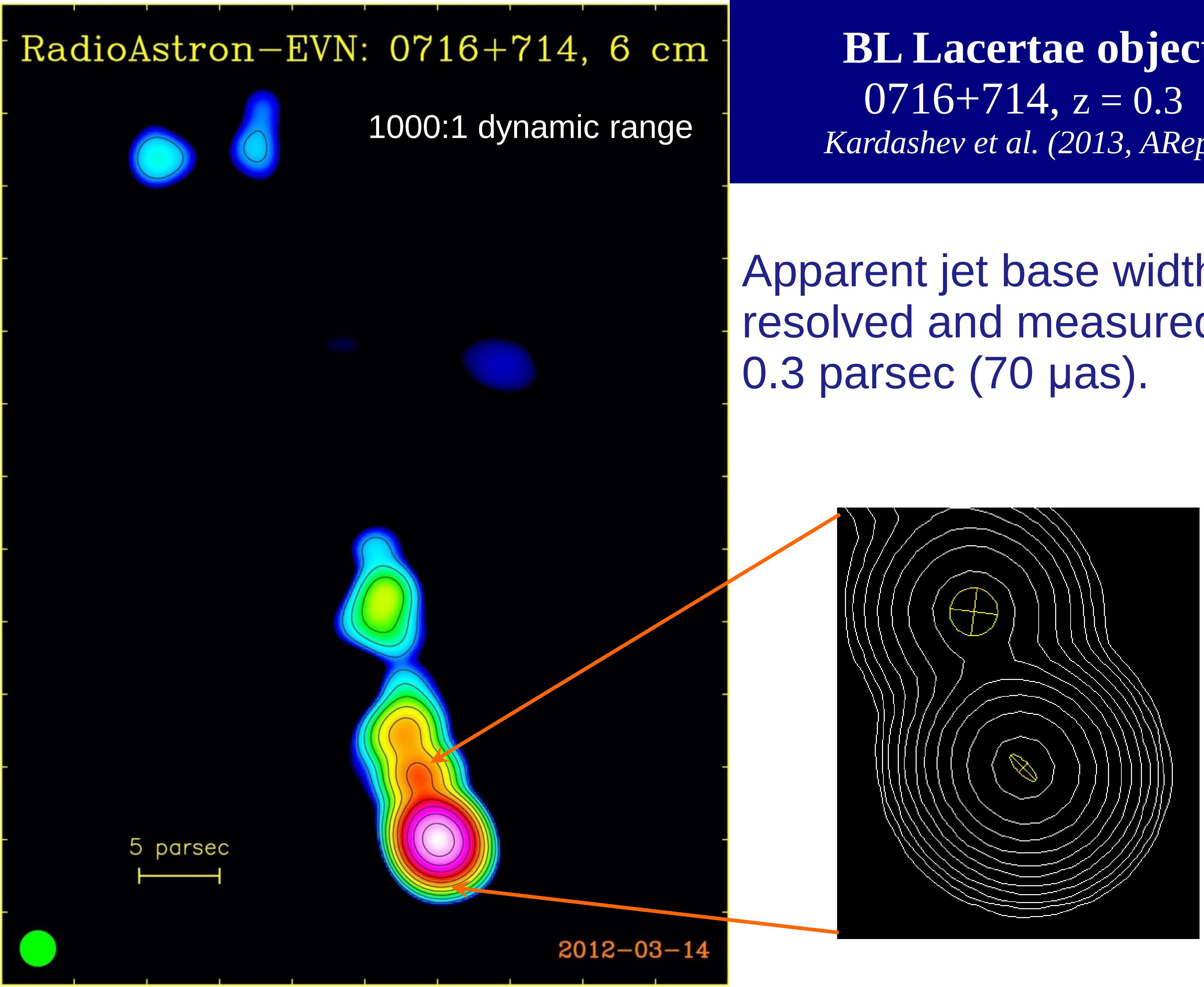
The inner jet structure is clearly resolved, a short counter jet is detected



Y.Y.Kovalev et al, ApJ, **668**, L27 (2007)

BL Lacertae object
0716+714, $z = 0.3$
Kardashev et al. (2013, ARep)

Apparent jet base width is resolved and measured as: 0.3 parsec (70 µas).

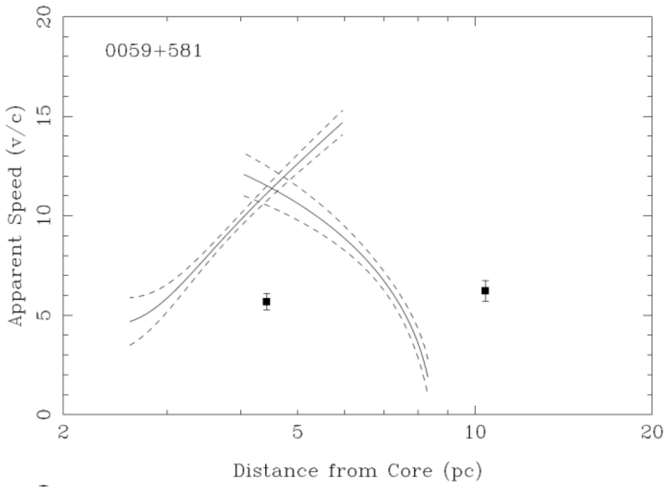


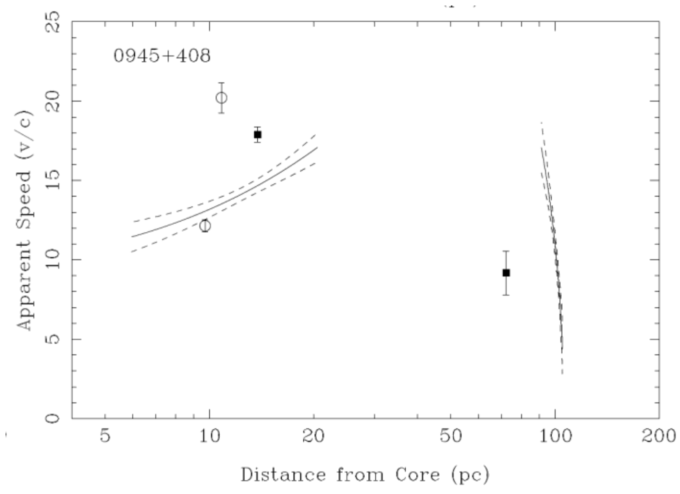
Internal structure – AGN

Homan, D. C. et al, ApJ, **789**, 134 (2015)

Acceleration at small distances,

decceleration at large distances.

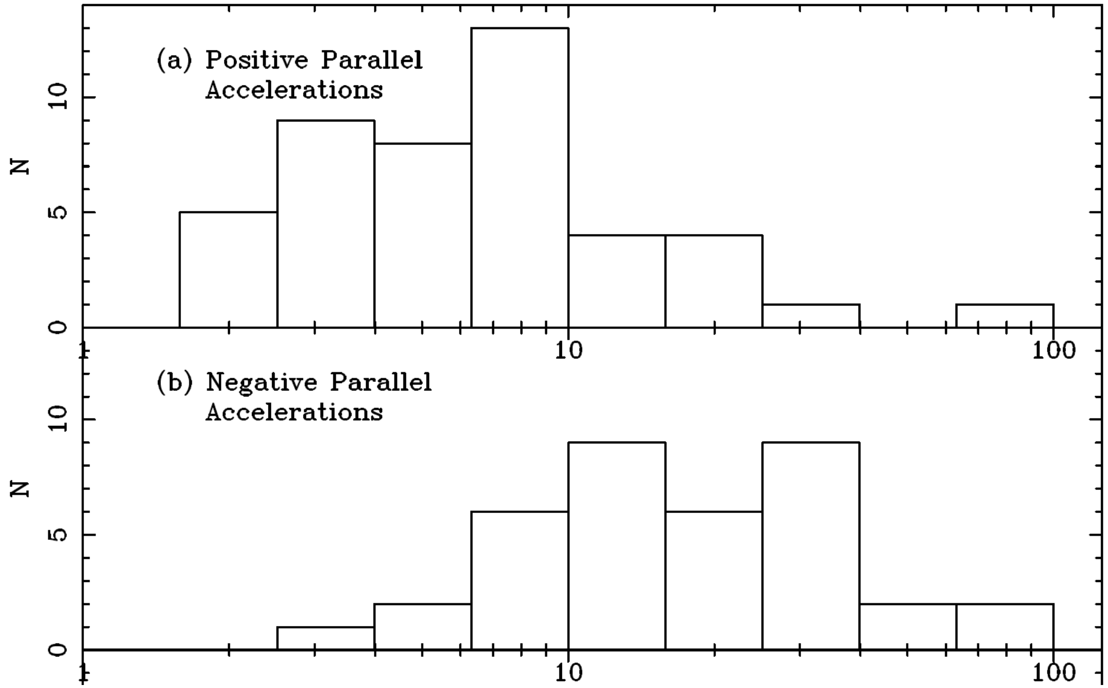




Internal structure – AGN

Homan, D. C. et al, ApJ, **789**, 134 (2015)

Acceleration at small distances,
decceleration at large distances.



pc (projection)

Internal structure – AGN

Main new observational results

- Acceleration along the jet at small distances

$$\dot{\Gamma} / \Gamma = 10^{-3}\ \mathrm{yr}^{-1}$$

- Deceleration at larger distances

- Collimation parameter

$$\Gamma\theta \sim 0.1$$

Jets – theory

- It is necessary to include external media into consideration. It is the ambient pressure that determines jet transverse scale and particle energy.

- Simple asymptotic solutions for the bulk Lorentz-factor.

- Transverse profile of the poloidal magnetic field.

- Magnetization – multiplication connection.

Jets – theory

Main parameters

- Michel magnetization parameter (maximal bulk Lorentz-factor)

$$\sigma_{\mathrm{M}} = \frac{\Omega^2 \Psi_{\mathrm{tot}}}{8\pi^2 c^2 \mu\eta}$$

μ now

- Multiplicity parameter

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

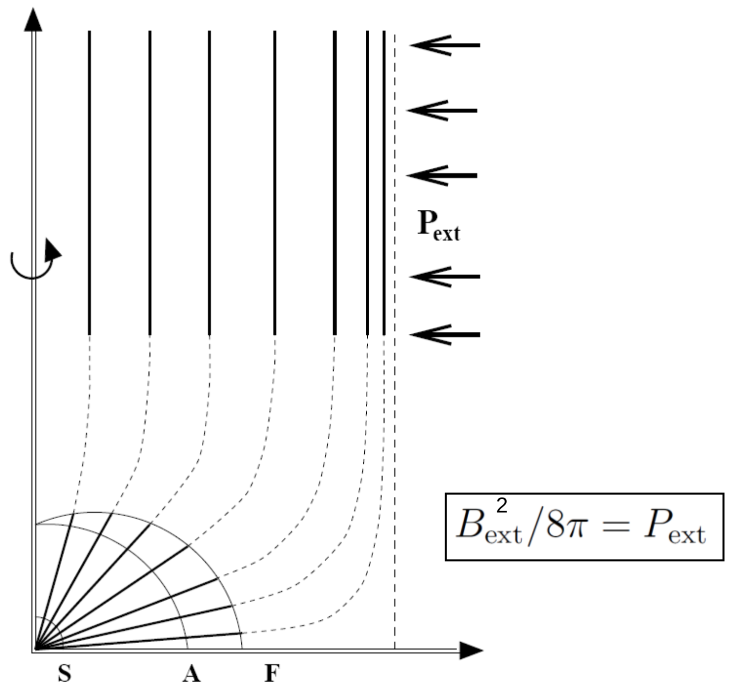
$$\rho_{\mathrm{GJ}} = -\frac{\mathbf{\Omega} \cdot \mathbf{B}}{2\pi c}$$

Jets – theory

- It is necessary to include the <u>external media</u> into consideration. It is the ambient pressure that determines the jet transverse scale and particle energy.

1D approach for cylindrical jets

$$\begin{cases} \dfrac{\mathrm{d}\mathcal{M}^2}{\mathrm{d}r_\perp} = F_1(\mathcal{M}^2, \Psi, r_\perp) \\ \dfrac{\mathrm{d}\Psi}{\mathrm{d}r_\perp} = F_2(\mathcal{M}^2, \Psi, r_\perp) \end{cases}$$



VB, L.M.Malyshkin. Astron. Lett., **26**, 208 (2000)
VB. Phys. Uspekhi, **40**, 659 (1997)

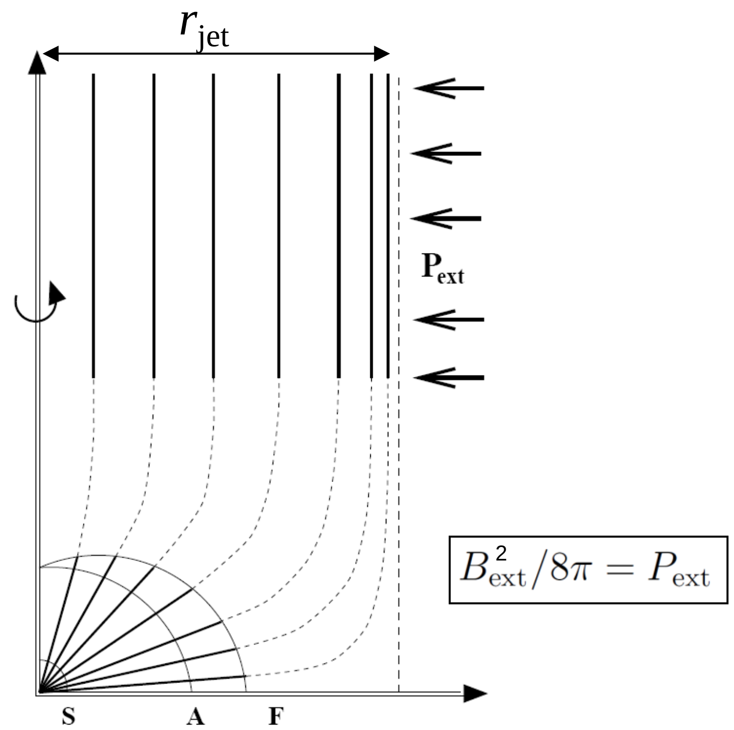
T.Lery, J.Heyvaerts, S.Appl, C.A.Norman. A&A, **347**, 1055 (1999)

Jets – theory

- It is necessary to include the <u>external media</u> into consideration. It is the ambient pressure that determines the jet transverse scale and particle energy.

$$r_{\rm jet} \sim R \left(\frac{B_{\rm in}^2}{8\pi P_{\rm ext}} \right)^{1/4}$$

$$\boxed{\frac{W_{\rm part}}{W_{\rm tot}} \sim \frac{1}{\sigma_{\rm M}} \left[\frac{B^2(R_{\rm L})}{8\pi P_{\rm ext}} \right]^{1/4}}$$

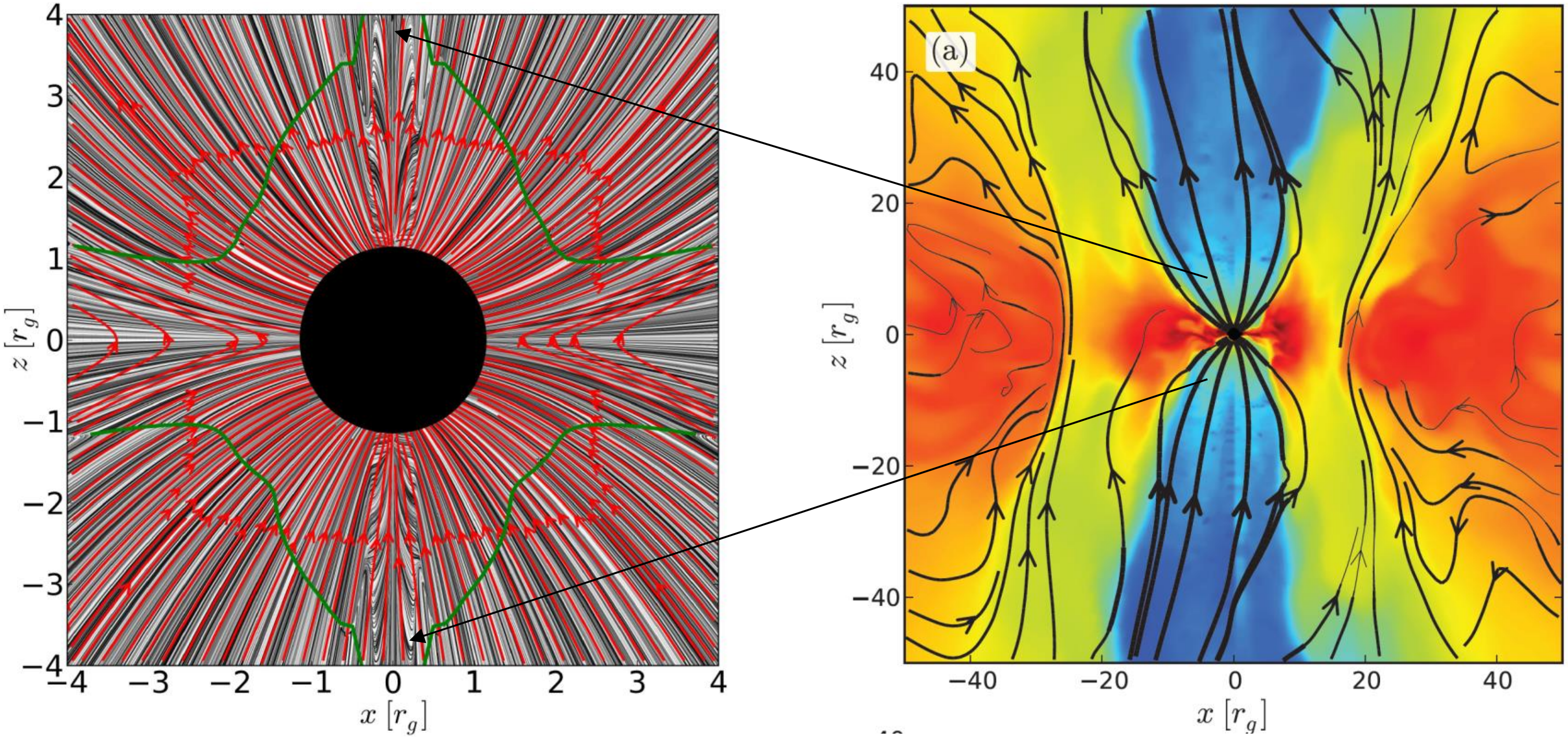


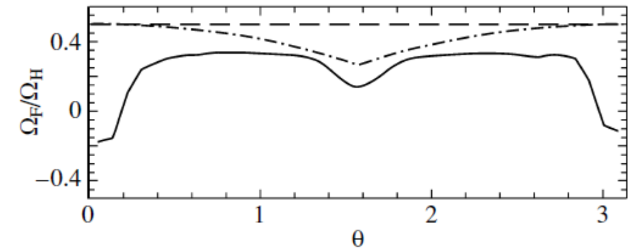
VB, L.M.Malyshkin. Astron. Lett., **26**, 208 (2000)
VB. Phys. Uspekhi, **40**, 659 (1997)

T.Lery, J.Heyvaerts, S.Appl, C.A.Norman. A&A, **347**, 1055 (1999)

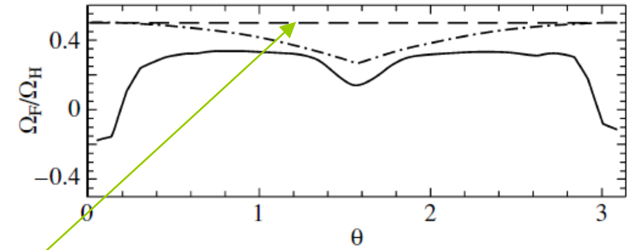
J.C.McKinney, A.Tchekhovskoy, R.D.Blandford. MNRAS, **423**, 3083 (2012)

Parabolic?





R.Blandford & R.Znajek. MNRAS, **179**, 433 (1977)

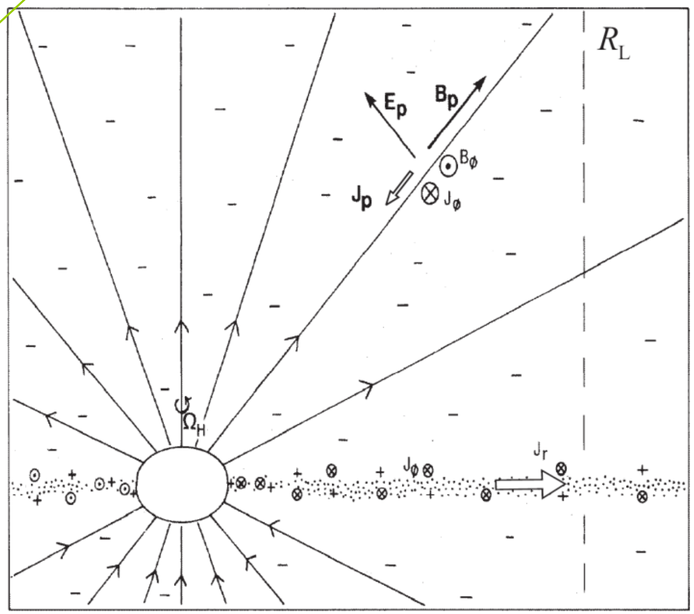


Monopole + Monopole

$$\Psi_0^{(2)} = \Psi_0(1 - \cos\theta).$$

Horizon ‘boundary condition’

$$4\pi I(\theta) = [\Omega_{\rm H} - \Omega_{\rm F}(\theta)]\Psi_0 \sin^2\theta.$$



At large distances

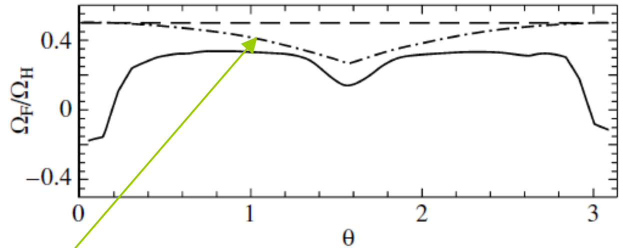
$$4\pi I(\theta) = \Omega_{\rm F}(\theta)\Psi_0 \sin^2\theta.$$

Then

$$\Omega_{\rm F} = \frac{\Omega_{\rm H}}{2}, \qquad I(\Psi) = I_{\rm M} = \frac{\Omega_{\rm F}}{4\pi}\left(2\Psi - \frac{\Psi^2}{\Psi_0}\right).$$

$$E_{\hat\theta} = -B_{\hat\varphi}$$

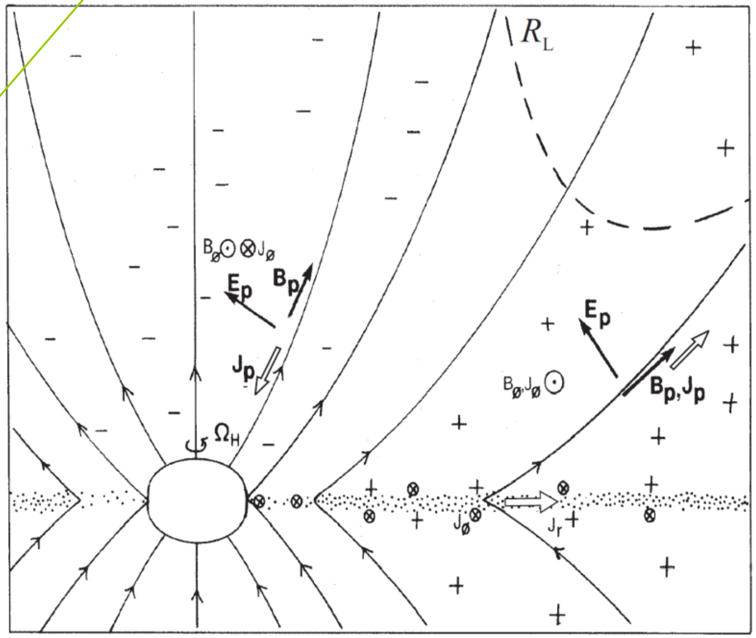
R.Blandford & R.Znajek. MNRAS, **179**, 433 (1977)



Parabolic + Parabolic

$$\Psi_0^{(1)}(r,\theta) = r(1-\cos\theta) + r_g(1+\cos\theta)[1-\ln(1+\cos\theta)] - 2r_g(1-\ln 2)$$

Horizon 'boundary condition'



$$4\pi I(\Psi) = [\Omega_H - \Omega_F(\Psi)]\sin\theta\frac{d\Psi}{d\theta}$$

At large distances

$$4\pi I(\theta) = \Omega_F(\theta)\Psi_0\sin^2\theta.$$

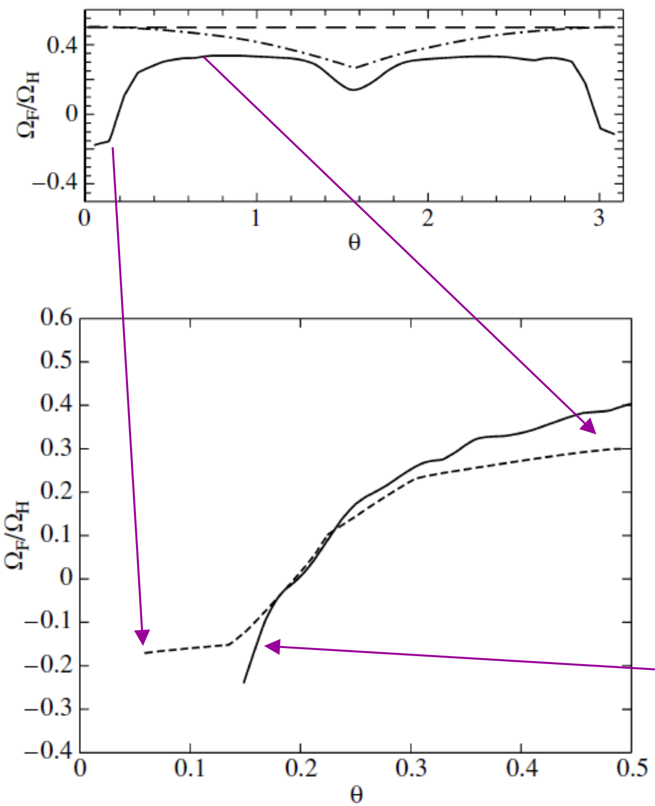
Then

$$\Omega_F(r_g,\theta) = \frac{\Omega_H\sin^2\theta[1+\ln(1+\cos\theta)]}{4\ln 2+\sin^2\theta+[\sin^2\theta-2(1+\cos\theta)]\ln(1+\cos\theta)}$$

Excellent agreement with analytical force-free behaveour

VB, A.A.Zheltoukov. Astron. Lett., **39**, 215 (2013)

Monopole + Cylinder



$$\begin{cases} A_1(\Psi) = \varpi^2 B_z \\ A_2(\Psi) = c^2 \displaystyle\int_0^{\varpi} x^2 \frac{d}{dx} (B_z)^2 \, dx \\ A_3(\Psi) = \dfrac{1}{2\pi} \sin\theta \dfrac{r_g^2 + a^2}{r_g^2 + a^2 \cos^2\theta} \left(\dfrac{d\Psi}{d\theta}\right) \end{cases}$$

$$\Omega_F = \Omega_H \left[\frac{A_3}{A_3 + A_1} + \frac{A_2}{\Omega_H^2 A_1 A_3 \left(1 + \sqrt{1 - \frac{A_2 (A_3^2 - A_1^2)}{\Omega_H^2 A_1^2 A_3^2}}\right)} \right]$$

Jets – theory

Simple asymptotic solutions for Lorentz-factor

Quasi-cylindrical flows ($\Gamma < \sigma_M$)

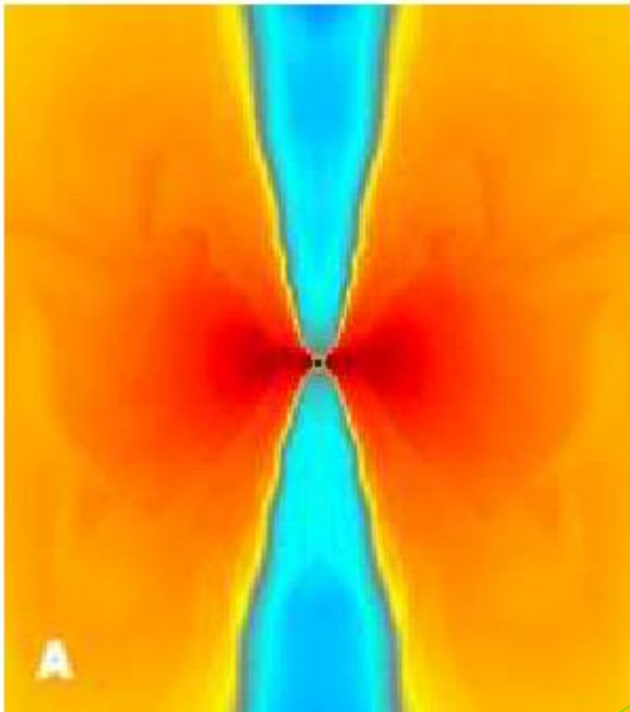
$$\boxed{\Gamma = x_r} \qquad x_r = \Omega_{\rm F} r_\perp / c$$

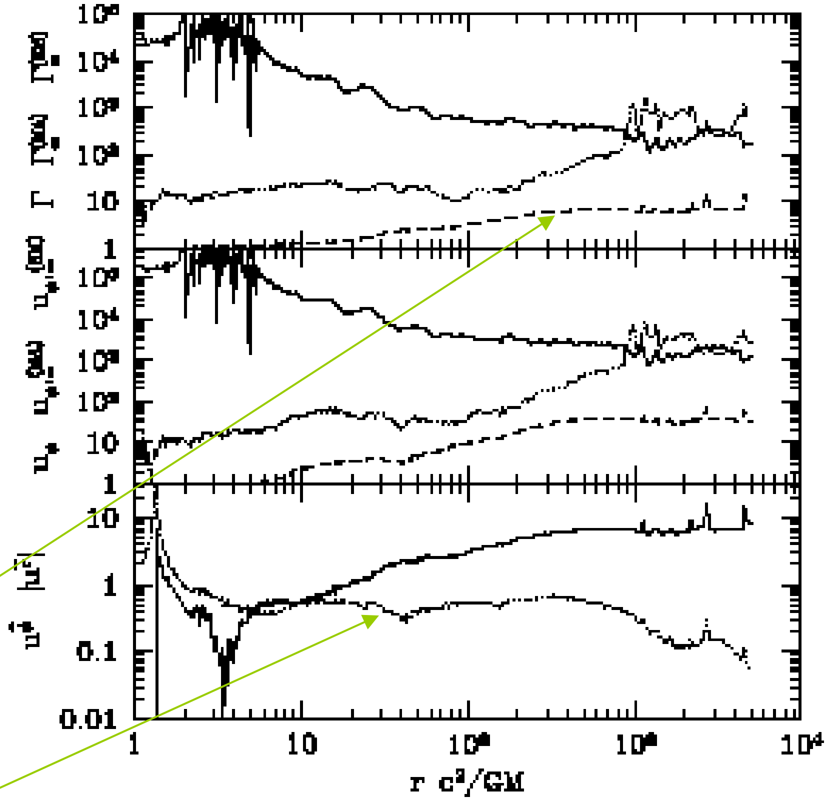
Quasi-radial flows

$$\boxed{\Gamma = C\sqrt{\frac{R_{\rm c}}{r_\perp}}}$$

Jets – theory

J.McKinney. MNRAS, **367**, 1797 (2006)





$$\Gamma(z) = (z/R_L)^{1/2},\ u_\varphi = 1$$

Jets – theory

Parabolic structure terminates the efficiency of acceleration

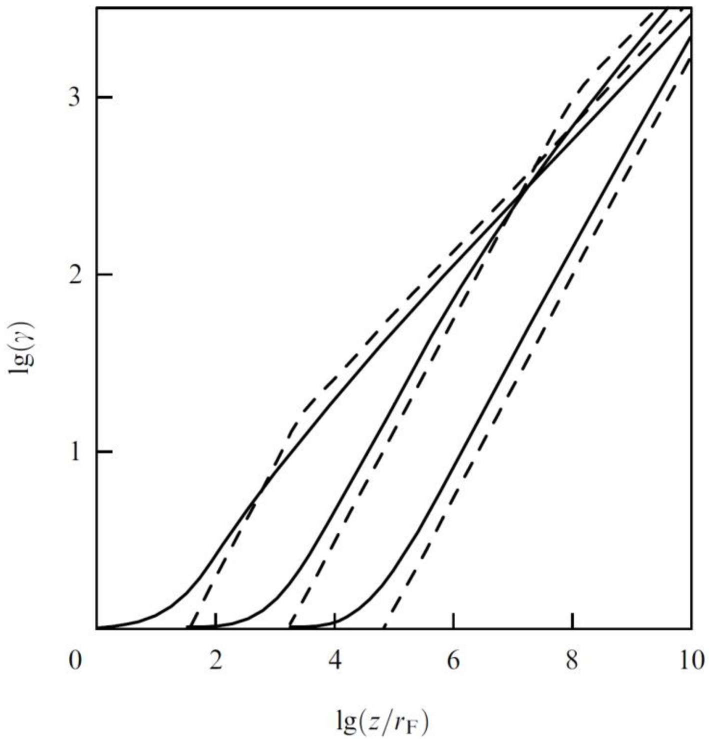
- Self-similar solution $z \sim r_{\perp}^{\ k}$
- For $k > 2$

$$\Gamma = x_r \sim z^{1/k}$$

- For $k < 2$

$$\Gamma = (R_c / r_{\perp})^{1/2} \sim z^{(k-1)/k}$$

- *Parabolic* $k = 2$



In all cases $\Gamma\theta \sim 1$

R. Narayan, J.McKinney, A.F.Farmer, MNRAS, **375**, 548, 2006

Jets – theory

Transverse profile of the poloidal magnetic field

T.Chiueh, Zh.-Yu.Li, M.C.Begelman. ApJ, **377**, 462 (1991)

D.Eichler. ApJ, **419**, 111 (1993)

S.V.Bogovalov. Astron. Lett., 21,565 (1995)

M.Camenzind. In Herbig-Haro Flows and the Birth of Low Mass Stars. Eds. Reipurth B., Bertout C. (1997)

$$B_{\rm p} = \frac{B_0}{1 + (r_\perp / r_{\rm core})^2}$$

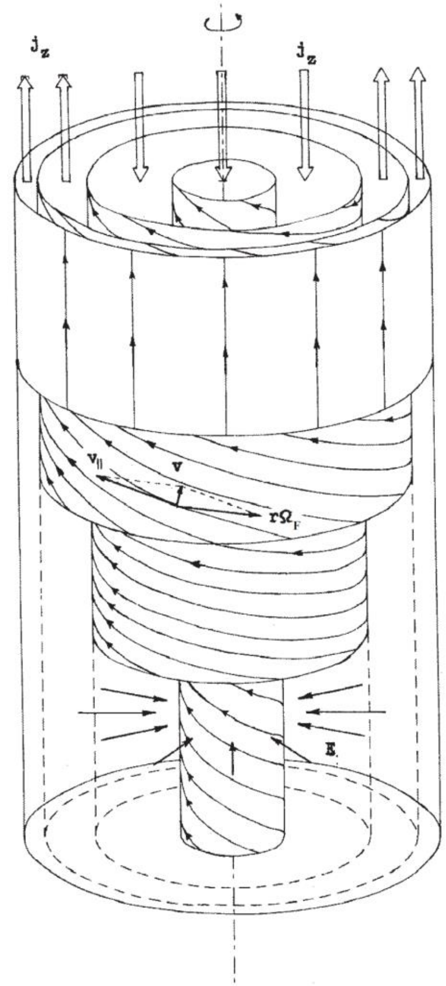
$$r_{\rm core} = \gamma_{\rm in} R_{\rm L}$$

Jets – theory

Transverse profile of the poloidal magnetic field

And this was odd, because…

homogeneneous poloidal magnetic field is the solution for magnetically dominated flow.



Jets – theory

Transverse profile of the poloidal magnetic field

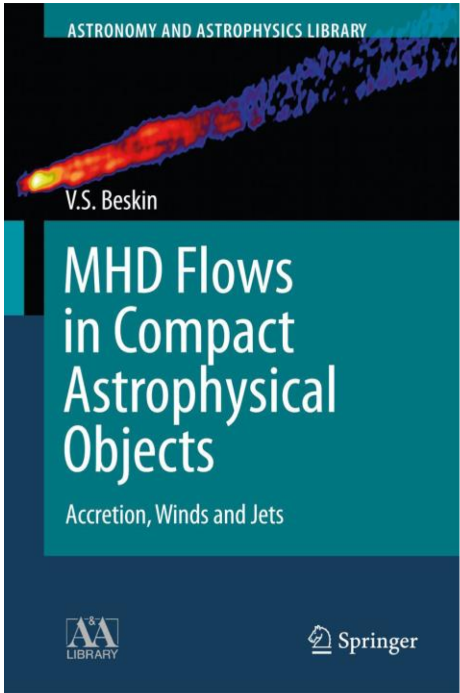
Theorem 5.2. *In the relativistic case, in the presence of the environment with rather high pressure ($B_{\rm ext} > B_{\rm min}$) the poloidal magnetic field inside the jet remains practically constant: $B_{\rm p} \approx B_{\rm ext}$. For small external pressure ($B_{\rm ext} < B_{\rm min}$) in the vicinity of the rotation axis there must form a core region $r_\perp < \varpi_{\rm c} = \gamma_{\rm in} R_{\rm L}$ with the magnetic field $B_{\rm p} \approx B_{\rm min}$ (5.69) containing only a small part of the total magnetic flux Ψ_0:*

$$\frac{\Psi_{\rm core}}{\Psi_0} \approx \frac{\gamma_{\rm in}}{\sigma}.$$

For $r_\perp < \varpi_{\rm c}$, the poloidal magnetic field $B_{\rm p}$ decreases as

$$B_{\rm p} \propto r_\perp^{\,2-\alpha},$$

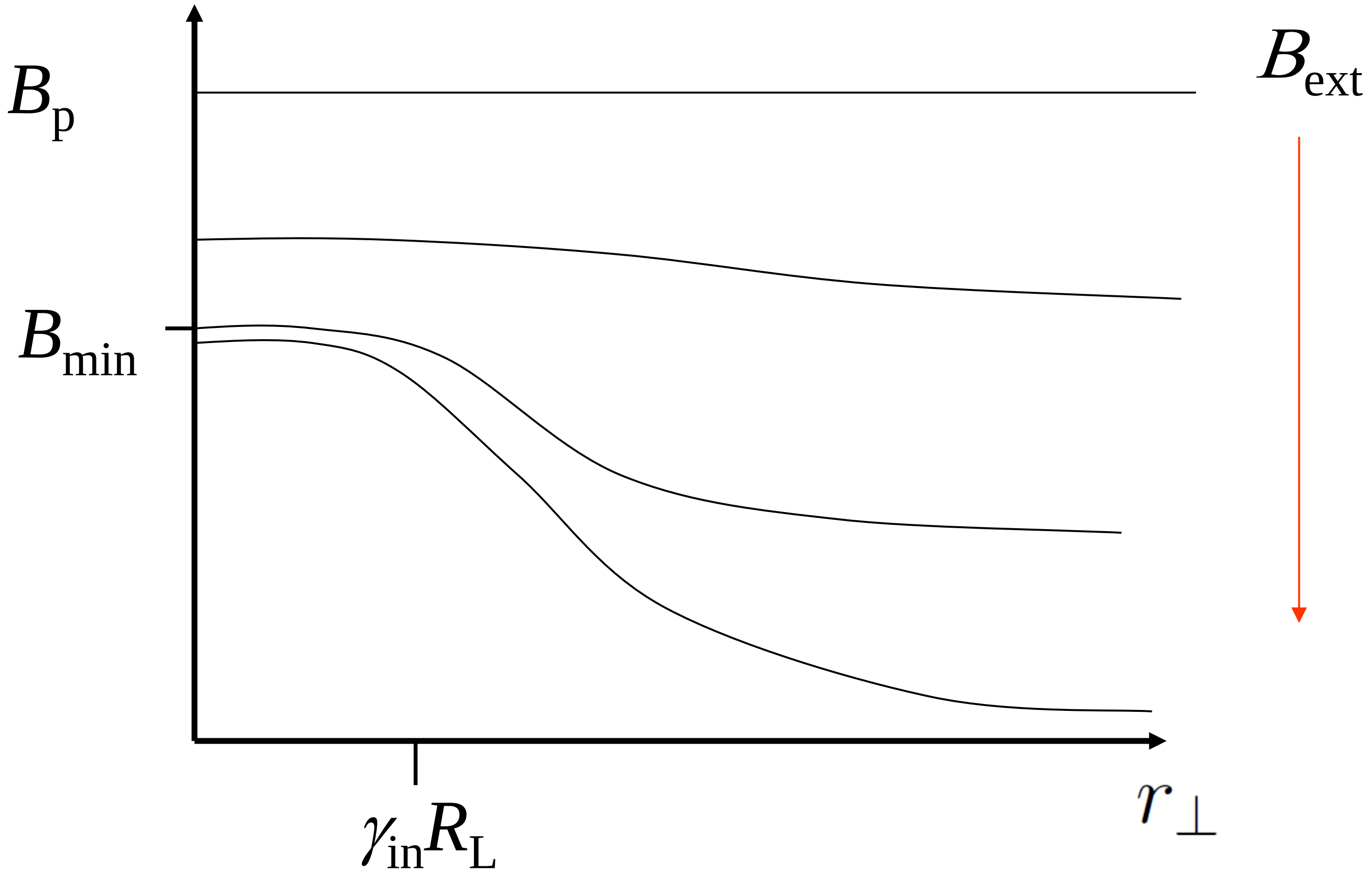
where $\alpha < 2$.



$$B_{\rm min} = \frac{1}{\sigma \gamma_{\rm in}} B(R_{\rm L}) \qquad B(R_{\rm L}) = \Omega^2 \Psi_{\rm tot}/\pi c^2 \qquad B_{\rm p}^2/8\pi \approx P_{\rm ext}$$

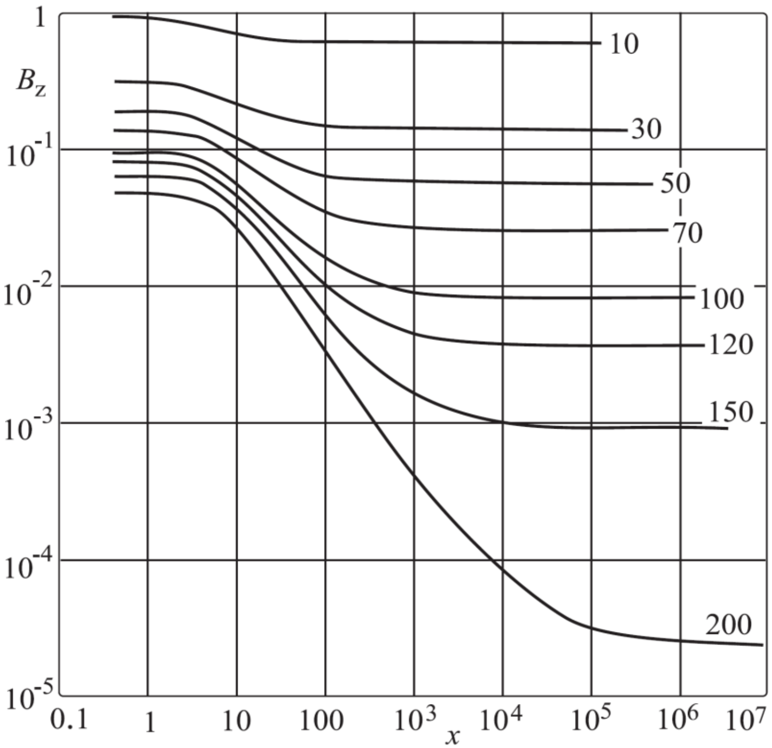
Central core

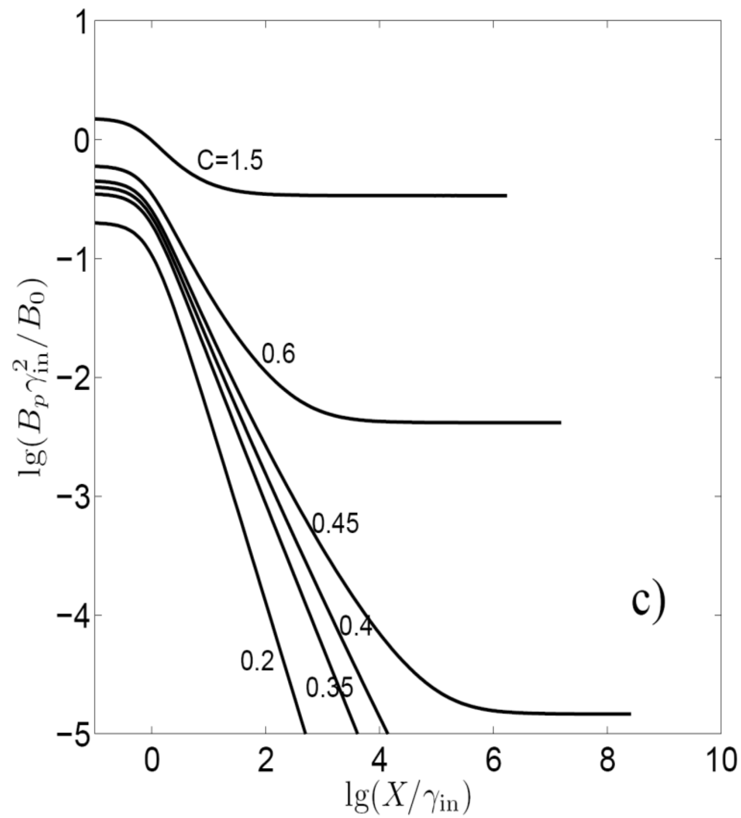
$$B_{\min} = \frac{1}{\sigma_M \gamma_{in}} B(R_L) \qquad r_{core} = \gamma_{in} R_L$$



Central core

$$\begin{cases} \dfrac{d\mathcal{M}^2}{dr_\perp} & = & F_1(\mathcal{M}^2, \Psi, r_\perp) \\ \dfrac{d\Psi}{dr_\perp} & = & F_2(\mathcal{M}^2, \Psi, r_\perp) \end{cases}$$

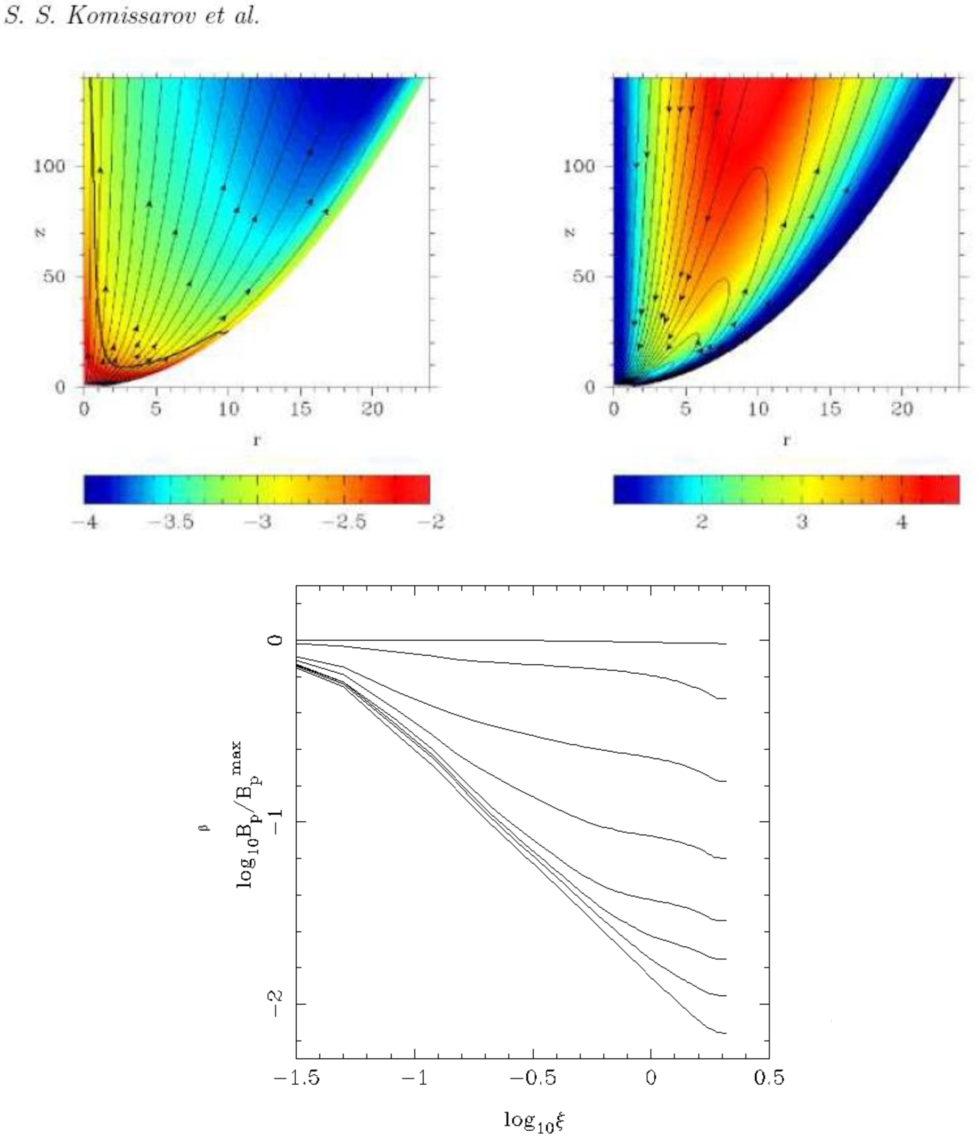




VB, E.E.Nokhrina.
MNRAS, **389**, 335 (2007)
MNRAS, **397**, 1486 (2009)

Yu.Lyubarsky. ApJ,
698, 1570 (2009)

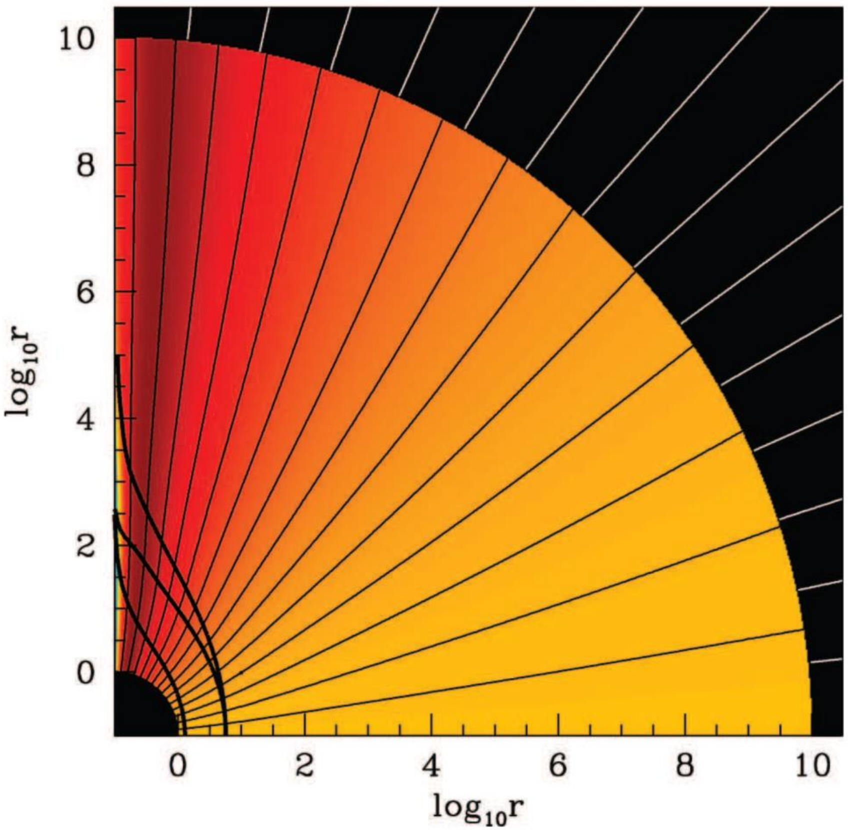
Central core

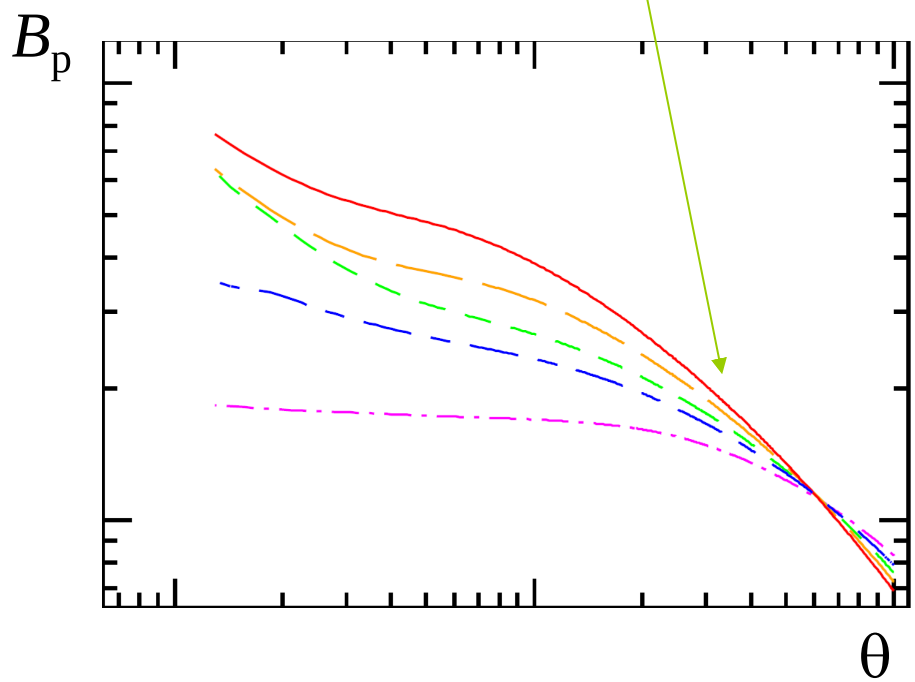


S.Komissarov, M.Barkov, N.Vlahakis, A.Königl. MNRAS, **380**, 51 (2006)

Central core

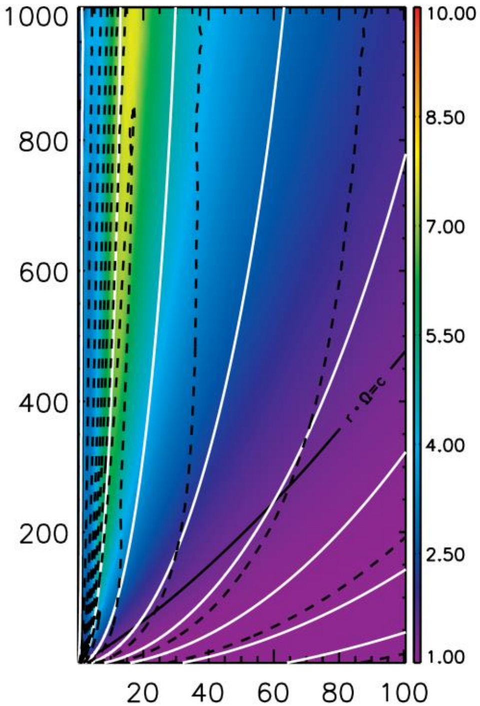
$$B_{\rm min} = \frac{1}{\sigma_{\rm M}\gamma_{\rm in}} B(R_{\rm L})$$

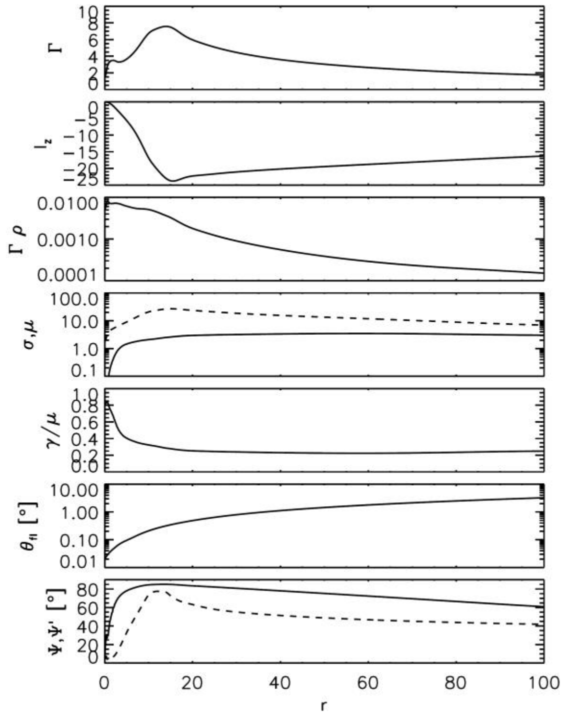


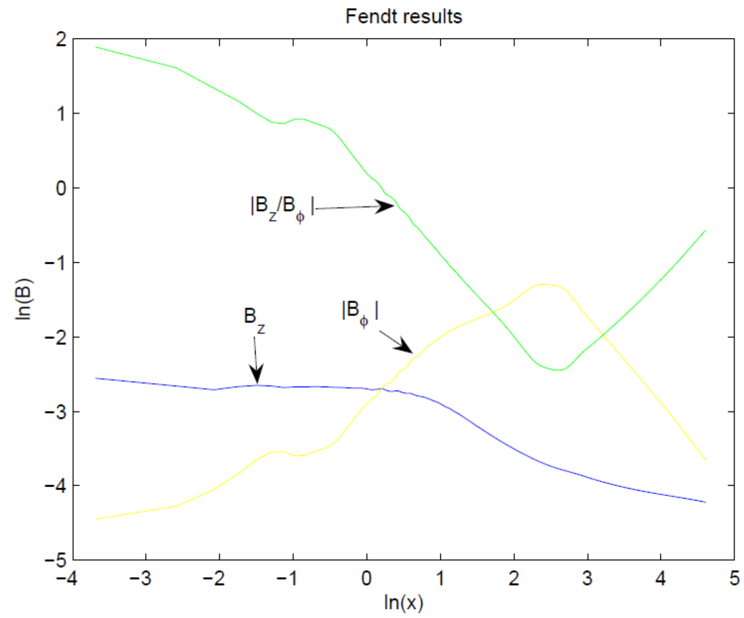


A.Tchekhovskoy, J.McKinney, R.Narayan. ApJ, **699**, 1789 (2009)

Central core







O.Porth, Ch.Fendt, Z.Meliani, B.Vaidya. ApJ, **737**, 42 (2011)

Jets – theory

$$\sigma_{\mathrm{M}} = \frac{\Omega^2 \Psi_{\mathrm{tot}}}{8\pi^2 c^2 \mu\eta}$$

Magnetization – multiplication connection

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

MHD 'central engine' energy losses

$$W_{\mathrm{tot}} \approx \left(\frac{\Omega R_0}{c}\right)^2 B_0^2 R_0^2 c$$

After some algebra

$$\sigma_{\mathrm{M}} \sim \frac{1}{\lambda}\left(\frac{W_{\mathrm{tot}}}{W_{\mathrm{A}}}\right)^{1/2}$$

$$W_{\mathrm{A}} = m_{\mathrm{e}}^2 c^5 / e^2 \approx 10^{17}\,\mathrm{erg\,s^{-1}}$$

Jets – theory

- Black hole mass evaluation

$$\begin{cases} W_{\rm tot} \approx \left(\dfrac{\Omega R_0}{c}\right)^2 B_0^2 R_0^2 c \\ r_{\rm jet} \sim R \left(\dfrac{B_{\rm in}^2}{8\pi P_{\rm ext}}\right)^{1/4} \end{cases}$$

If $B_0 \sim B_{\rm in}\,,\ R_0 \sim R \sim r_{\rm g} = GM/c^2$

$$M \approx 10^9\, M_\odot \left(\frac{r_{\rm jet}}{1\,{\rm pc}}\right)^2 \left(\frac{B_{\rm ext}}{10^{-6}\,{\rm Gs}}\right) \left(\frac{W_{\rm tot}}{10^{44}\,{\rm erg/s}}\right)^{-1/2}$$

Jets – theory

- Real parameters

$$\begin{cases} \sigma_{\rm M} \sim \dfrac{1}{\lambda}\left(\dfrac{W_{\rm tot}}{W_{\rm A}}\right)^{1/2} \\ W_{\rm A} = m_{\rm e}^2 c^5/e^2 \approx 10^{17}\,{\rm erg\,s^{-1}} \end{cases}$$

$$\sigma_{\rm M}\lambda \sim 10^{14}$$

- As $\Gamma = r_{\rm jet} / R_{\rm L} \sim 10^4 - 10^5$, there are two possibilities:

  1. Magnetically dominated flow

$$\sigma_{\rm M} > 10^5 \qquad \Gamma \sim 10^4 - 10^5$$

  2. Saturation regime

$$\sigma_{\rm M} < 10^5 \qquad \Gamma \sim \sigma_{\rm M}$$

Core shift and jet parameters

E.E.Nokhrina, VB, Y.Y.Kovalev, A.A.Zheltoukhov. MNRAS, **447,** 2726 (2015)

- No assumption about equipartition (in both cases we know the bulk particle energy Γmc^2).

$$\Gamma \sim \sigma_M$$

- The only free parameter is the fraction of synchrotron radiating particles $n_{\rm syn} = \xi n_{\rm e}$.

$$\xi \approx 0.01$$

$$\lambda = 7.3 \times 10^{13} \left(\frac{\eta}{\rm mas\,GHz}\right)^{3/4} \left(\frac{D_{\rm L}}{\rm Gpc}\right)^{3/4} \times \left(\frac{\chi}{1+z}\right)^{3/4} \frac{1}{(\delta \sin\varphi)^{1/2}} \frac{1}{(\xi \gamma_{\rm min})^{1/4}}$$

$$\sigma_{\rm M} = 1.4 \left[\left(\frac{\eta}{\rm mas\,GHz}\right)\left(\frac{D_{\rm L}}{\rm Gpc}\right)\frac{\chi}{1+z}\right]^{-3/4} \times \sqrt{\delta \sin\varphi}\,(\xi \gamma_{\rm min})^{1/4} \sqrt{\frac{P_{\rm jet}}{10^{45}\ {\rm erg\ s^{-1}}}}$$

Core shift and jet parameters

E.E.Nokhrina, VB, Y.Y.Kovalev, A.A.Zheltoukhov. MNRAS, **447,** 2726 (2015)

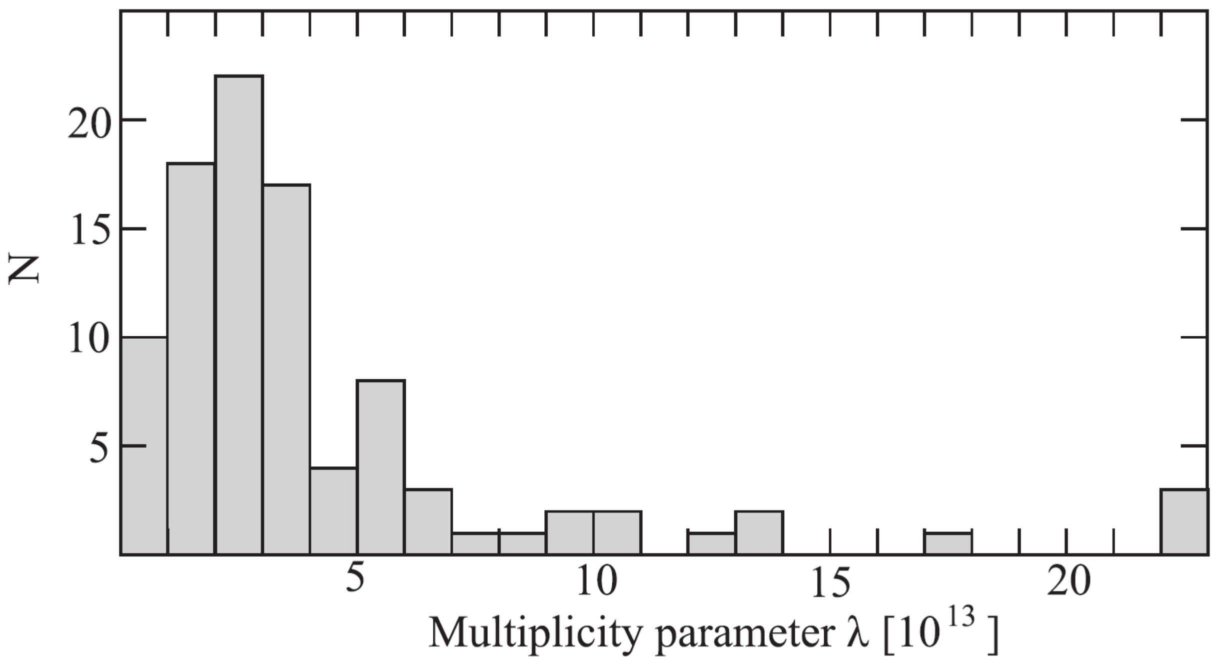


Figure 1. Distributions of the multiplicity parameter λ for the sample of 97 sources. Two objects with $\lambda = 2.8 \times 10^{14}$ and 3.6×10^{14} lie out of the shown range of values.

Core shift and jet parameters

E.E.Nokhrina, VB, Y.Y.Kovalev, A.A.Zheltoukhov. MNRAS, **447,** 2726 (2015)

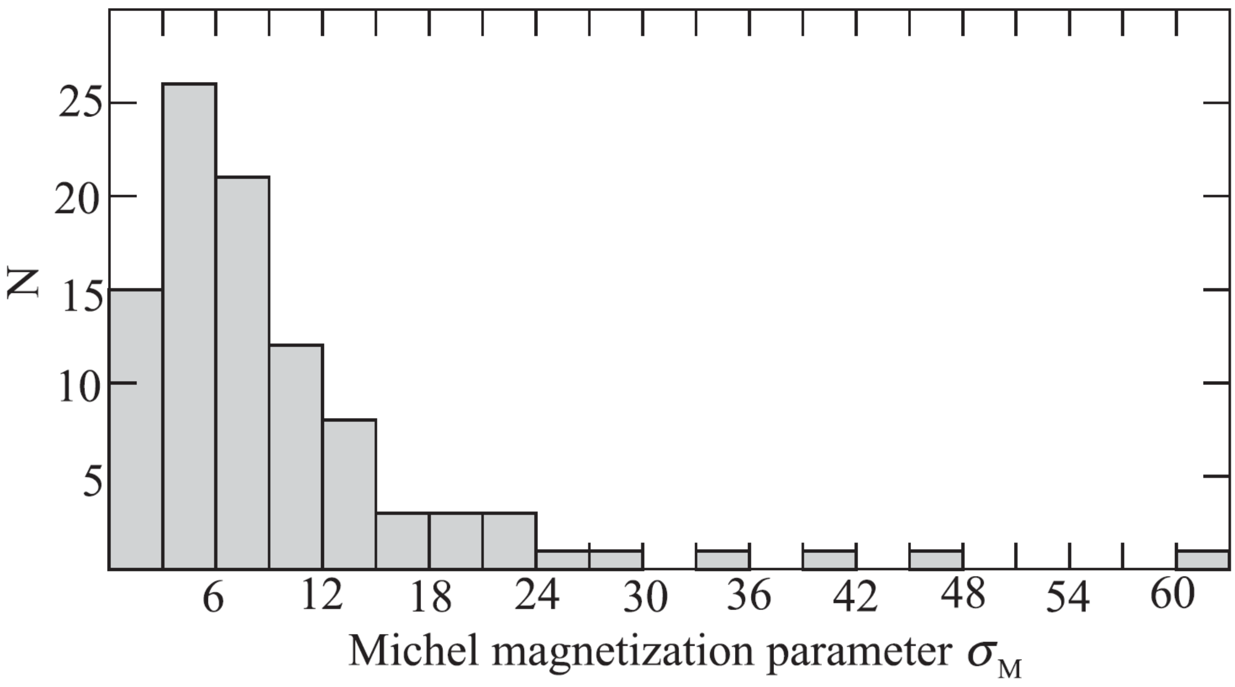


Figure 2. Distributions of the Michel magnetization parameter σ_M for the sample of 97 sources.

Core shift and jet parameters

E.E.Nokhrina, VB, Y.Y.Kovalev, A.A.Zheltoukhov. MNRAS, **447,** 2726 (2015)

$$\begin{cases} \dfrac{\mathrm{d}\mathcal{M}^2}{\mathrm{d}r_\perp} & = & F_1(\mathcal{M}^2, \Psi, r_\perp) \\ \dfrac{\mathrm{d}\Psi}{\mathrm{d}r_\perp} & = & F_2(\mathcal{M}^2, \Psi, r_\perp) \end{cases}$$

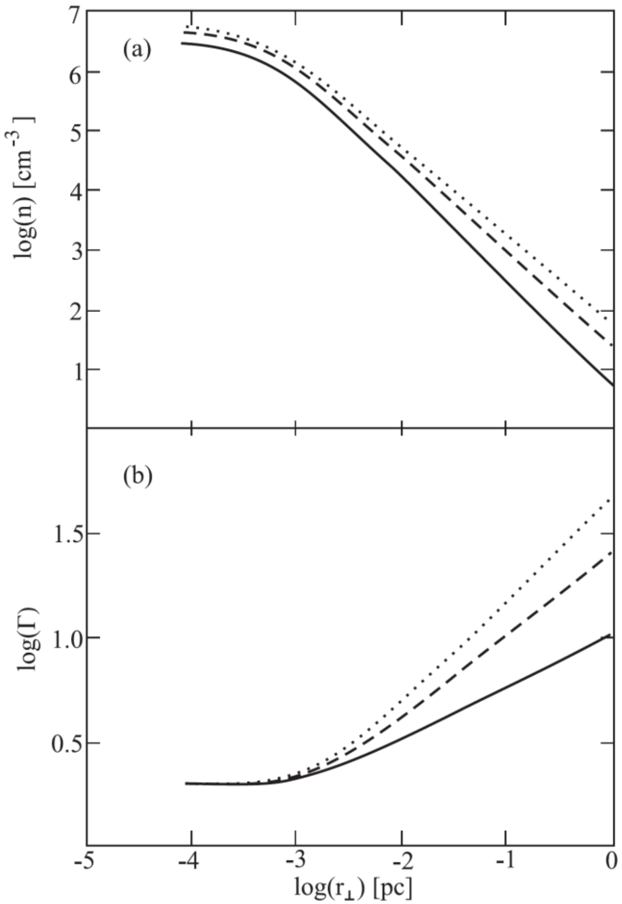


Figure 3. Transversal profile of the number density n_e (a) and Lorentz factor Γ (b) in logarithmical scale for $\lambda = 10^{13}$, jet radius $R_{jet} = 1$ pc and three different values of σ: 5 (solid line), 15 (dashed line) and 30 (dotted line).

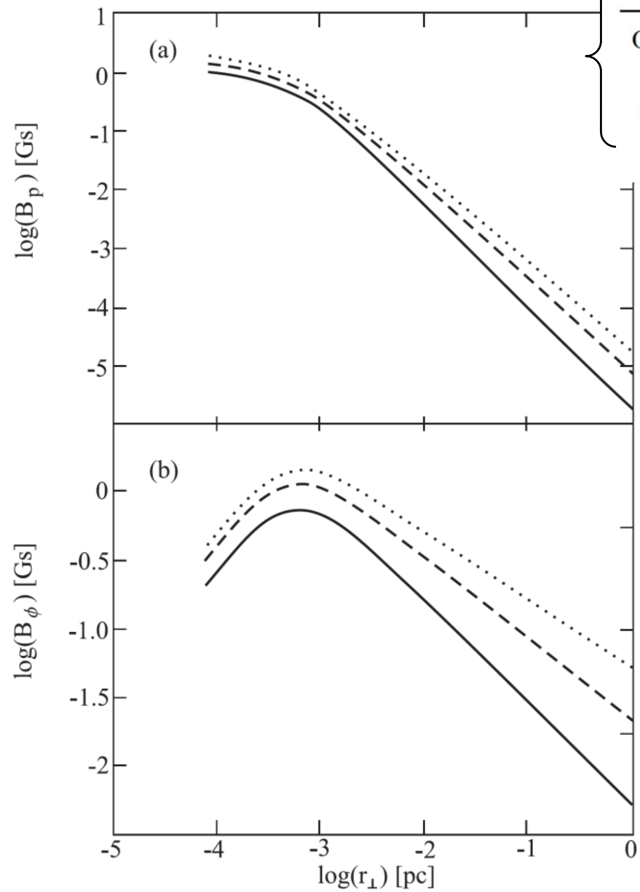


Figure 4. Transversal profile of poloidal (a) and toroidal (b) components of magnetic field in logarithmical scale for the same parameters and line types as in Fig. 3.

Core shift and jet parameters

E.E.Nokhrina, VB, Y.Y.Kovalev, A.A.Zheltoukhov. MNRAS, **447,** 2726 (2015)

Slow acceleration along the jet

$$\dot{\Gamma} / \Gamma = 10^{-3}\ \mathrm{yr}^{-1}$$

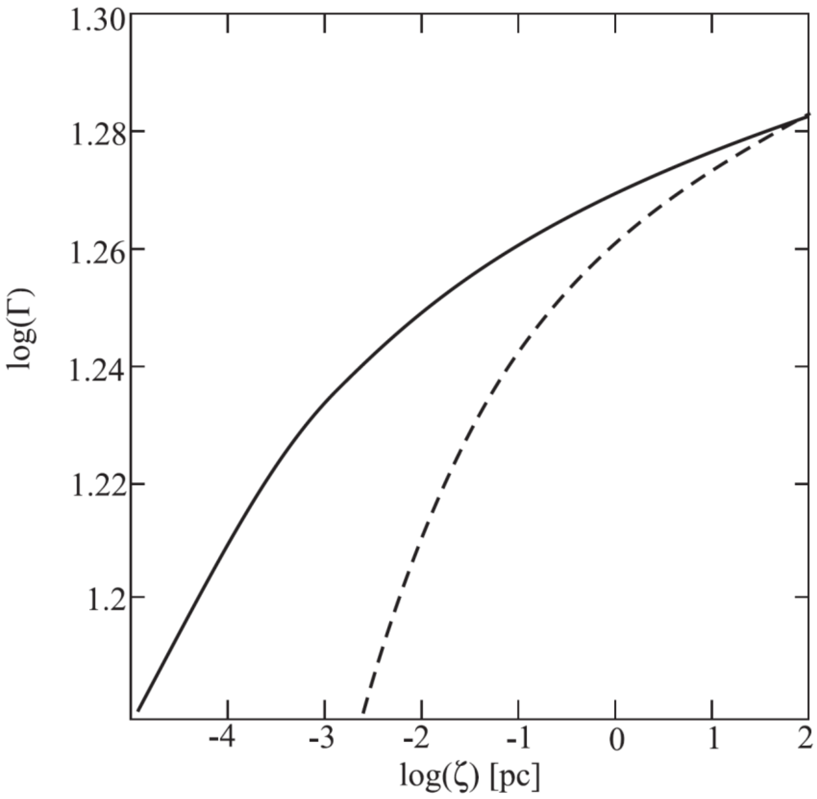


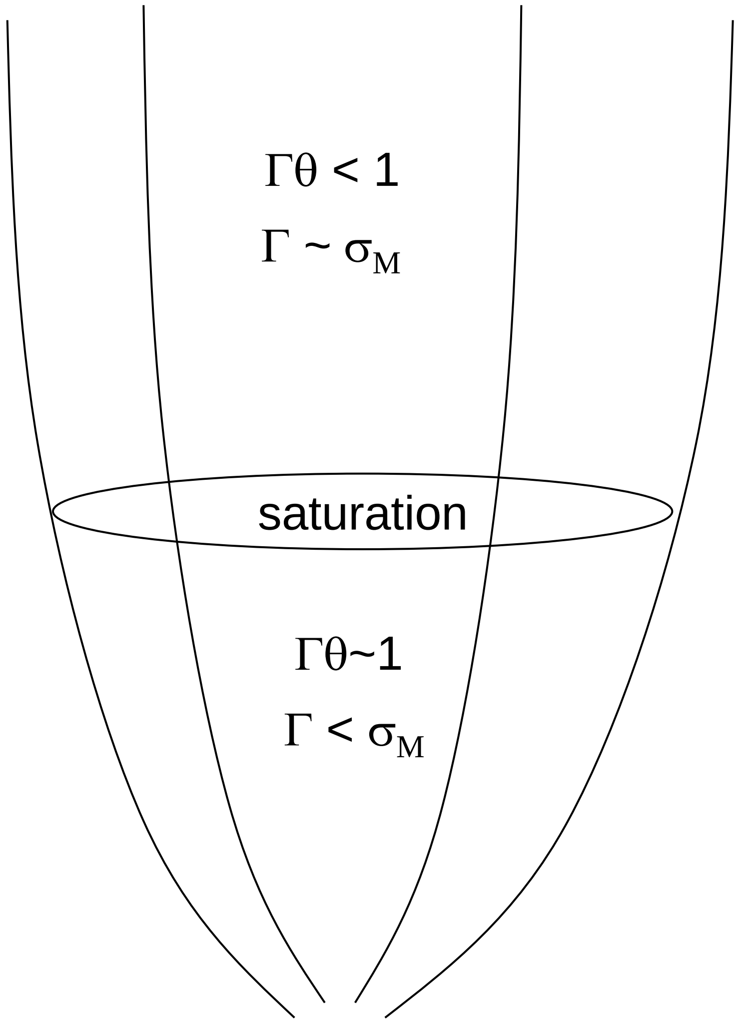
Figure 5. Dependence of Lorentz factor on coordinate along the jet in assumption of $\zeta \propto r_{\perp}^{3}$ (solid line) and $\zeta \propto r_{\perp}^{2}$ (dashed line) form of the jet.

Collimation parameter

For magnetically dominated flow
the theory prediction is

$$\Gamma\theta \sim 1$$

But in the saturation regime
($\Gamma \sim \text{const}$) $\quad \Gamma\theta \sim 0.1$
becomes possible.



Main conclusions

- Saturation
- Central core

Deceleration

Photon drag

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Particle loading

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Poster

On the Deceleration of Relativistic Jets in Active Galactic Nuclei

VB, A.V.Chernoglazov, E.E.Nokhrina, N.Zakamska

On the deceleration of relativistic jets in active galactic nuclei

Photon drag

1. Expression for $U_{\rm cr}$ is actually the same for particle and magnetically dominated flows.
2. $U_{\rm cr}$ is even lower than CMB energy density. Does it mean that the radiation drag is really so important?

$$U_{\rm cr} = \frac{m_{\rm e}c^2}{\sigma_{\rm T} L \Gamma}$$

Particle loading

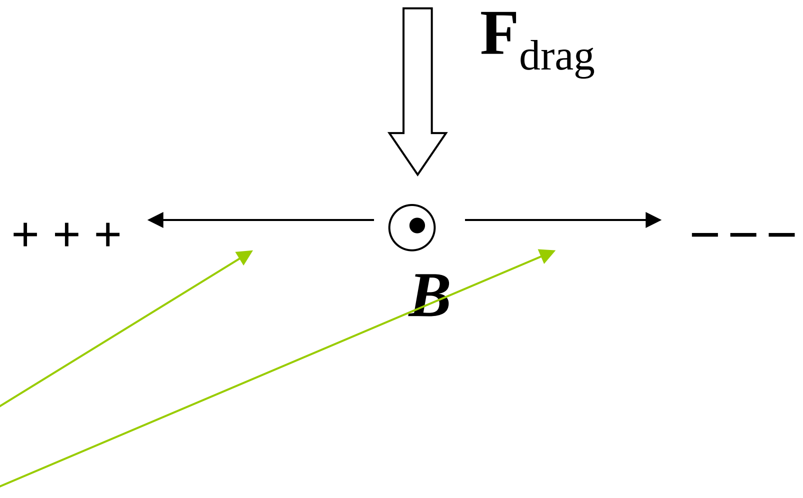
1. The loading results in the formation of a media with highly anisotropic pressure.
2. The redistribution of charges changing the electric field is important. This implies that now is not an integral of motion.
3. The critical number density can be even smaller than MHD number density.

$$n_{\rm cr} = \frac{B_{\varphi}^2}{m_{\rm e}c^2\Gamma^2}$$

Photon drag

MHD flow + isotropic radiation field

Physics (in the comoving reference frame)

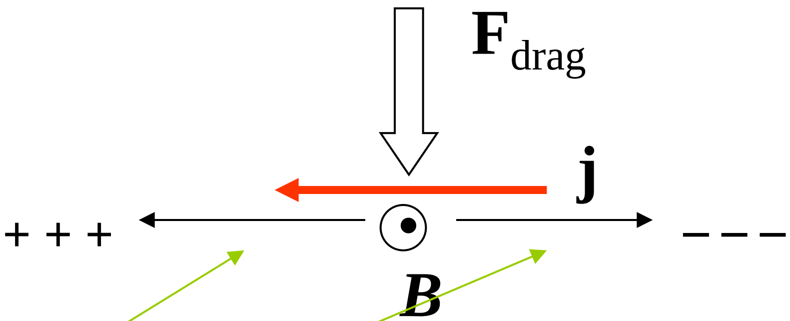


$$\mathbf{U}_{\rm dr} = c\frac{\mathbf{F}_{\rm drag} \times \mathbf{B}}{eB^2}$$

Photon drag

MHD flow + isotropic radiation field

Physics (in the comoving reference frame)

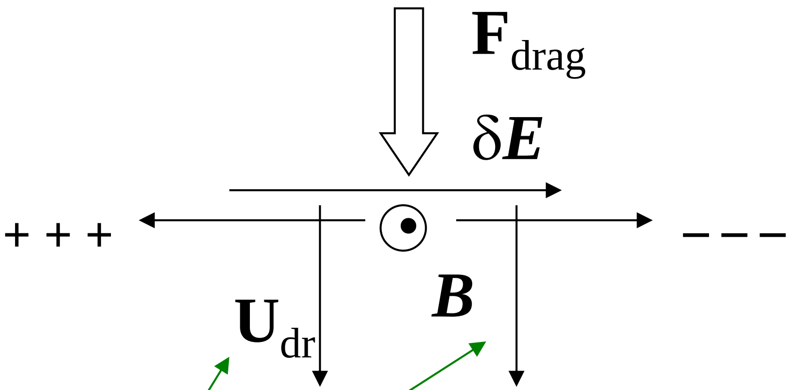


$$\mathbf{U}_{\rm dr} = c\frac{\mathbf{F}_{\rm drag}\times\mathbf{B}}{eB^2}$$

Photon drag

MHD flow + isotropic radiation field

Physics (in the comoving reference frame)



$$\mathbf{U}_{\rm dr} = c\frac{\mathbf{E}\times\mathbf{B}}{B^2}$$

Photon drag

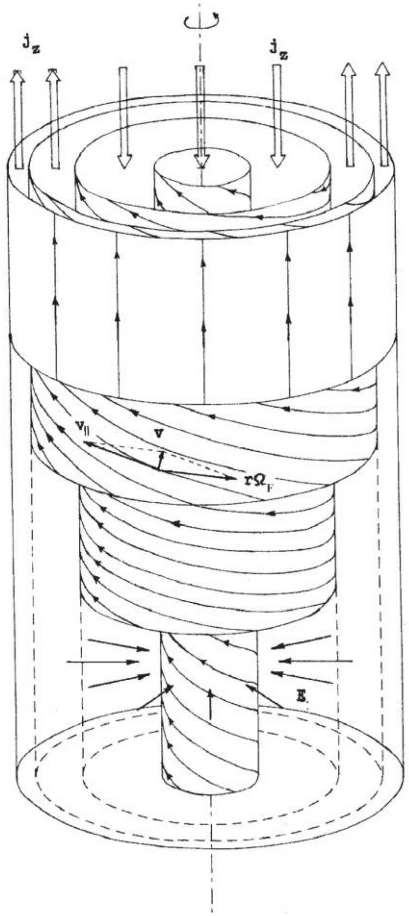
MHD flow + radiation field

How the photon drag affects the MHD flow

- MHD cylindrical jet
- electron-positron plasma
- isotropic photon field $U_{\rm iso}$

$$(\mathbf{v}^{\pm}\nabla)\mathbf{p}^{\pm} = e\left(\mathbf{E}+\frac{\mathbf{v}^{\pm}}{c}\times\mathbf{B}\right)+\mathbf{F}^{\pm}_{\rm drag}$$

$$\mathbf{F}^{\pm}_{\rm drag} = -\frac{4}{3}\frac{\mathbf{v}}{v}\sigma_T U_{\rm iso}(\gamma^{\pm})^2$$



Photon drag

MHD flow + isotropic radiation field

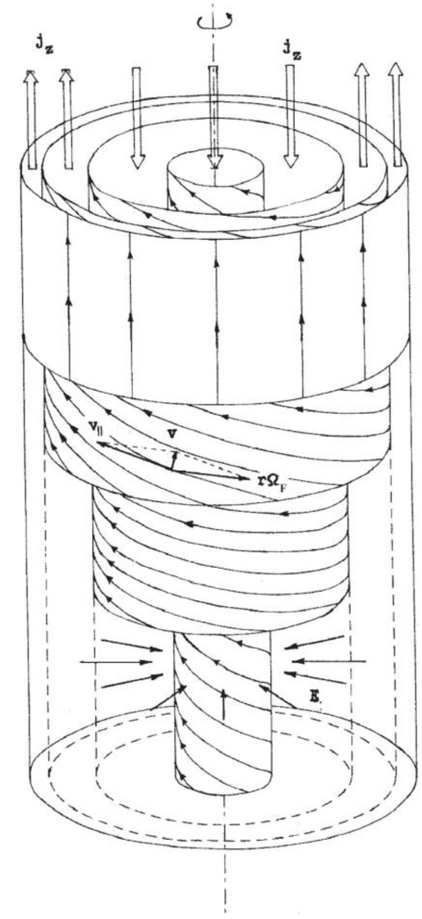
Zero force-free approximation

$$v_z^0 = c, \quad v_\varpi^0 = 0, \quad v_\varphi^0 = 0$$

$$\left\{ \begin{array}{lcl} \mathbf{B} & = & \dfrac{\nabla\Psi \times \mathbf{e}_\varphi}{2\pi\varpi} - \dfrac{2I}{c\varpi}\mathbf{e}_\varphi, \\ \mathbf{E} & = & -\dfrac{\Omega_{\rm F}(\Psi)}{2\pi c}\nabla\Psi. \end{array} \right.$$

$$\boxed{4\pi I(\Psi) = 2\Omega_F(\Psi)\Psi}$$

$$B_z^0 = B_0$$



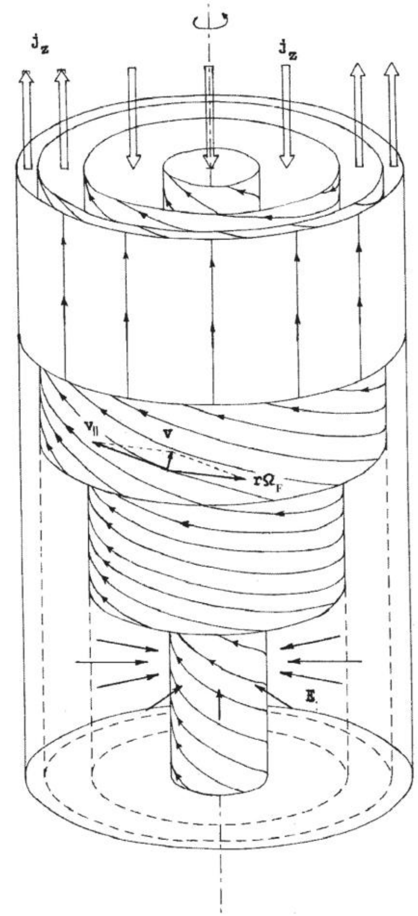
Photon drag

MHD flow + isotropic radiation field

MHD disturbances + drag

$$
\begin{aligned}
n^{+} &= \frac{\Omega_0 B_0}{2\pi c e}\left[\lambda - \frac{1}{4r_\perp}\frac{\mathrm{d}}{\mathrm{d}r_\perp}\left(r_\perp^2\frac{\Omega_{\mathrm{F}}}{\Omega_0}\right) + \eta^{+}(r_\perp, z)\right], \\
n^{-} &= \frac{\Omega_0 B_0}{2\pi c e}\left[\lambda + \frac{1}{4r_\perp}\frac{\mathrm{d}}{\mathrm{d}r_\perp}\left(r_\perp^2\frac{\Omega_{\mathrm{F}}}{\Omega_0}\right) + \eta^{-}(r_\perp, z)\right], \\
v_z^{\pm} &= c\left[1 - \xi_z^{\pm}(r_\perp, z)\right], \\
v_r^{\pm} &= c\xi_r^{\pm}(r_\perp, z), \\
v_\varphi^{\pm} &= c\xi_\varphi^{\pm}(r_\perp, z).
\end{aligned}
$$

$$
\begin{aligned}
B_r &= -\frac{\varepsilon}{2} r_\perp B_0 \frac{\partial f}{\partial z}, \\
B_\varphi &= \frac{\Omega_0 r_\perp}{c} B_0\left[-\frac{\Omega_{\mathrm{F}}}{\Omega_0} - \zeta(r_\perp, z)\right], \\
B_z &= B_0\left[1 + \frac{\varepsilon}{2r_\perp}\frac{\partial}{\partial r_\perp}\left(r_\perp^2 f\right)\right], \\
E_r &= \frac{\Omega_0 r_\perp}{c} B_0\left[-\frac{\Omega_{\mathrm{F}}}{\Omega_0} - \frac{1}{r_\perp}\frac{\partial}{\partial r_\perp}\left(r_\perp^2\delta\right)\right], \\
E_z &= -\frac{\Omega_0 r_\perp^2}{c} B_0 \frac{\partial \delta}{\partial z},
\end{aligned}
$$



Photon drag

MHD flow + isotropic radiation field

MHD disturbances + drag

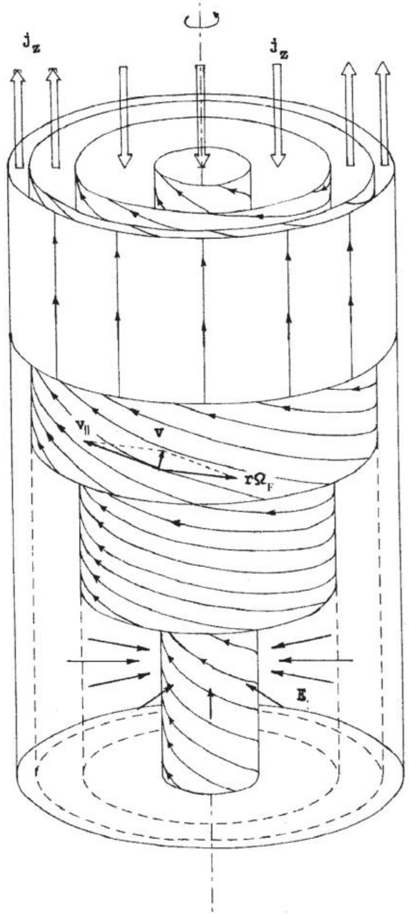
$$
\left\{
\begin{aligned}
&-\frac{1}{r_\perp}\frac{\partial}{\partial r_\perp}(r_\perp^2\zeta) = \\
&\quad 2(\eta^+ - \eta^-) - 2\left[(\lambda - K)\,\xi_z^+ - (\lambda + K)\,\xi_z^-\right], \\
&2(\eta^+ - \eta^-) + \frac{1}{r_\perp}\frac{\partial}{\partial r_\perp}\left[r_\perp\frac{\partial}{\partial r_\perp}\left(r_\perp^2\delta\right)\right] + r_\perp^2\frac{\partial^2\delta}{\partial z^2} = 0, \\
&r_\perp\frac{\partial\zeta}{\partial z} = 2\left[(\lambda - K)\,\xi_r^+ - (\lambda + K)\,\xi_r^-\right], \\
&-\varepsilon r_\perp^2\frac{\partial^2 f}{\partial z^2} - \varepsilon\frac{\partial^2}{\partial r_\perp^2}\left(r_\perp^2 f\right) = \\
&\quad 4\,\frac{\Omega_0 r_\perp}{c}\left[(\lambda - K)\,\xi_\varphi^+ - (\lambda + K)\,\xi_\varphi^-\right], \\
&\frac{\partial}{\partial z}\left(\xi_r^+\gamma^+\right) = -\xi_r^+ F_{\rm d}(\gamma^+)^2 \\
&\quad +4\,\frac{\lambda\sigma_{\rm M}}{r_{\rm jet}^2}\left[-\frac{\partial}{\partial r_\perp}(r_\perp^2\delta) + r_\perp\zeta - r_\perp\frac{\Omega_{\rm F}}{\Omega_0}\xi_z^+ + \frac{c}{\Omega_0}\xi_\varphi^+\right], \\
&\frac{\partial}{\partial z}\left(\xi_r^-\gamma^-\right) = -\xi_r^- F_{\rm d}(\gamma^-)^2 \\
&\quad -4\,\frac{\lambda\sigma_{\rm M}}{r_{\rm jet}^2}\left[-\frac{\partial}{\partial r_\perp}(r_\perp^2\delta) + r_\perp\zeta - r_\perp\frac{\Omega_{\rm F}}{\Omega_0}\xi_z^- + \frac{c}{\Omega_0}\xi_\varphi^-\right], \\
&\frac{\partial}{\partial z}\left(\gamma^+\right) = -F_{\rm d}(\gamma^+)^2 + 4\,\frac{\lambda\sigma_{\rm M}}{r_{\rm jet}^2}\left(-r_\perp^2\frac{\partial\delta}{\partial z} - r_\perp\frac{\Omega_{\rm F}}{\Omega_0}\xi_r^+\right), \\
&\frac{\partial}{\partial z}\left(\gamma^-\right) = -F_{\rm d}(\gamma^-)^2 - 4\,\frac{\lambda\sigma_{\rm M}}{r_{\rm jet}^2}\left(-r_\perp^2\frac{\partial\delta}{\partial z} - r_\perp\frac{\Omega_{\rm F}}{\Omega_0}\xi_r^-\right), \\
&\frac{\partial}{\partial z}\left(\xi_\varphi^+\gamma^+\right) = -\xi_\varphi^+ F_{\rm d}(\gamma^+)^2 \\
&\quad +4\,\frac{\lambda\sigma_{\rm M}}{r_{\rm jet}^2}\left(-\frac{\varepsilon}{2}\frac{c r_\perp}{\Omega_0}\frac{\partial f}{\partial z} - \frac{c}{\Omega_0}\xi_r^+\right), \\
&\frac{\partial}{\partial z}\left(\xi_\varphi^-\gamma^-\right) = -\xi_\varphi^- F_{\rm d}(\gamma^-)^2 \\
&\quad -4\,\frac{\lambda\sigma_{\rm M}}{r_{\rm jet}^2}\left(-\frac{\varepsilon}{2}\frac{c r_\perp}{\Omega_0}\frac{\partial f}{\partial z} - \frac{c}{\Omega_0}\xi_r^-\right).
\end{aligned}
\right.
$$

$$\sigma_{\rm M} = \frac{\Omega_0 e B_0 r_{\rm jet}^2}{4\lambda m c^3}$$

$$K = \frac{1}{4r_\perp}\frac{\rm d}{{\rm d}r_\perp}\left(r_\perp^2\frac{\Omega_{\rm F}}{\Omega_0}\right)$$

$$F_{\rm d} = \frac{4}{3}\frac{\sigma_{\rm T}U_{\rm iso}}{mc^2}$$

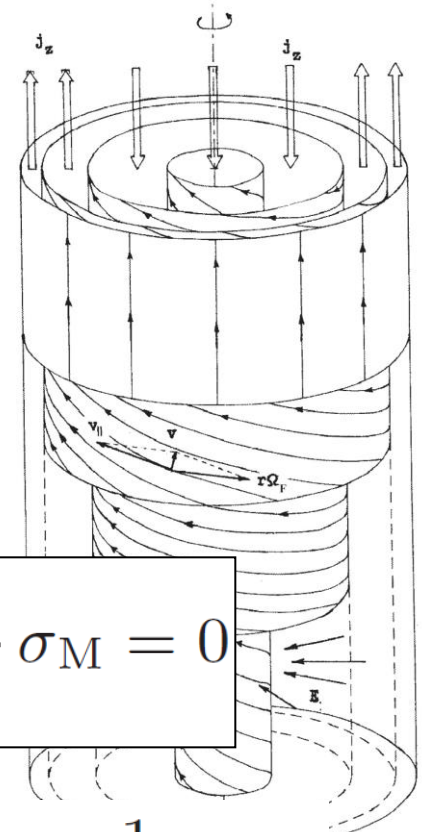
with N.Zakamska



Photon drag

MHD flow + isotropic radiation field

$$\frac{\partial}{\partial z}\left(\gamma^{+}+\gamma^{-}\right) = -(F_{\rm d}^{+}+F_{\rm d}^{-}) - \frac{eB_0\Omega r_\perp}{m_{\rm e}c^3}(\xi_r^{+}-\xi_r^{-})$$



Equation for Γ

$$2\Gamma^3 - 2\left(K' - \int_0^z F_{\rm d}\Gamma^2(z')\mathrm{d}z'\right)\Gamma^2 + \frac{x_r^2}{x_{\rm jet}^2}\sigma_{\rm M} = 0$$

$$K' = \Gamma_0 - \frac{x_r^2}{x_{\rm jet}^2}\sigma_{\rm M}\, r_\perp \frac{\mathrm{d}}{\mathrm{d}r_\perp}\left(\frac{\delta}{\Omega_{\rm F}/\Omega_0}\right) + \frac{1}{2x_{\rm jet}^2}\sigma_{\rm M}$$

Photon drag

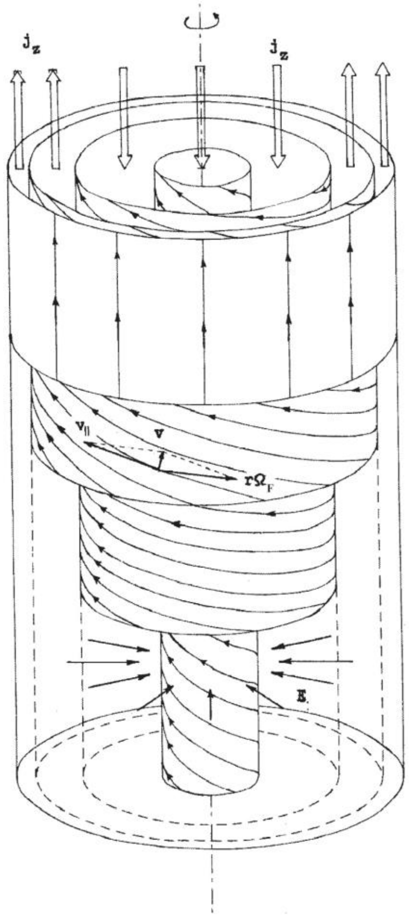
MHD flow + isotropic radiation field

Critical photon density $U_{\rm iso}$

$$\Gamma(z) \approx \frac{\Gamma_0}{1+\Gamma_0 \int F_{\rm d} {\rm d}z'}$$

$$F_{\rm d}^{\pm} = \frac{4}{3}\frac{\sigma_{\rm T} U_{\rm iso}}{mc^2}(\gamma^{\pm})^2$$

$$\boxed{U_{\rm cr} = \frac{m_{\rm e}c^2}{\sigma_{\rm T} L \Gamma}}$$



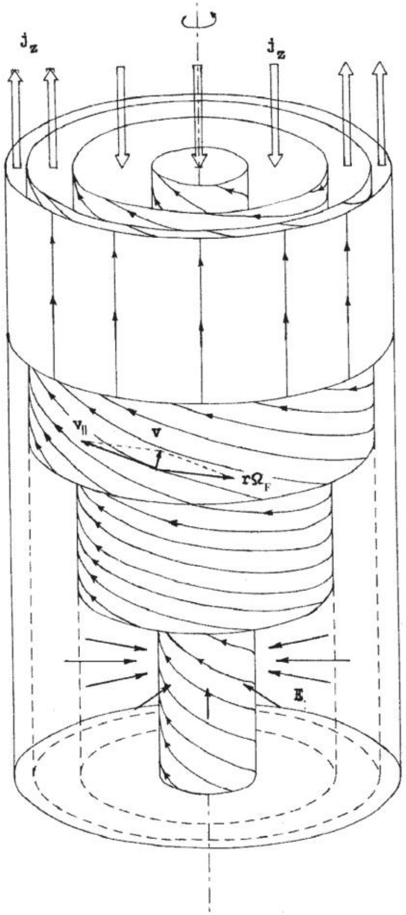
Loading

MHD flow + e^-e^+ pair creation

How the particle loading affects the MHD flow

- MHD cylindrical jet
- electron-positron plasma
- creation at rest

$$\frac{1}{\Gamma^2} = \frac{1}{x_r^2} + \frac{B_\varphi^2 - \mathbf{E}^2}{B_\varphi^2}$$



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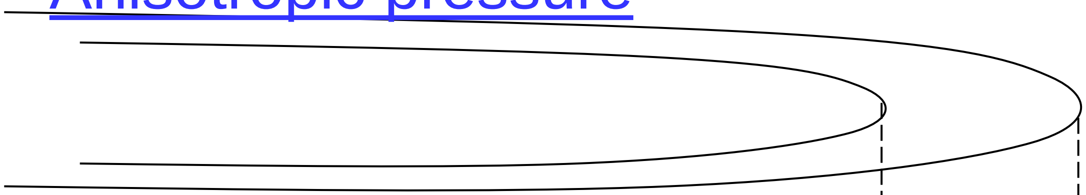
Anisotropic pressure



z – moving reference frame

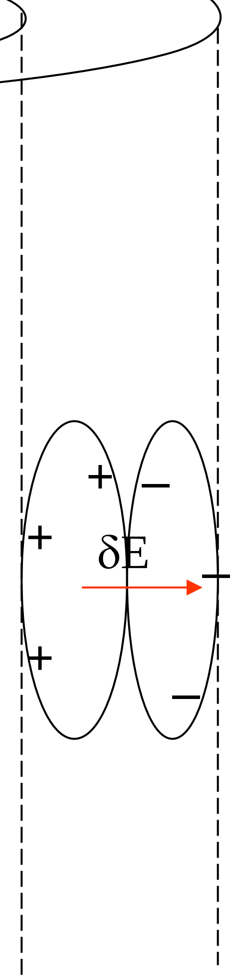
$$V = E_\theta / B_\varphi$$

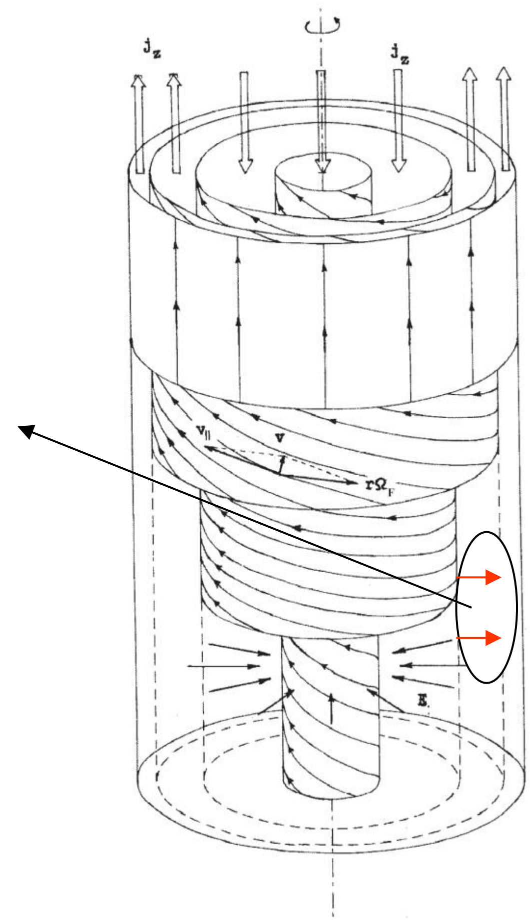
$$\Gamma = 1/(1 - V^2/c^2)^{1/2}$$

In this frame

$$B_\phi = B_\varphi/\Gamma,$$
$$B_z = B_{\rm p}.$$

$$\tan\alpha = B_z/B_\phi$$





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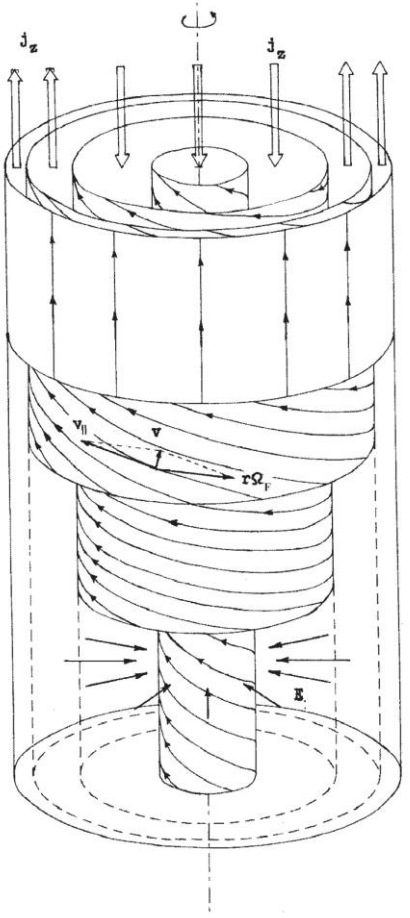
MHD flow + e⁻e⁺ pair creation (at rest)

M.Lyutikov (2005) – quasi-spherical

$$T^{ij} = (w + b^2) u^i u^j + \left(p + \frac{1}{2} b^2 \right) g^{ij} - b^i b^j$$

$$\begin{cases} \frac{1}{r^2}\partial_r [r^2 (w + b^2) \beta \gamma^2] = R \\ \frac{1}{r^2}\partial_r \{r^2 [(w + b^2)\beta^2\gamma^2 + (p + b^2/2)]\} - \frac{2p}{r} = 0 \\ \frac{1}{r}\partial_r [r b \beta \gamma] = 0 \\ \frac{1}{r^2}\partial_r [r^2 \rho \beta \gamma] = R \end{cases}$$



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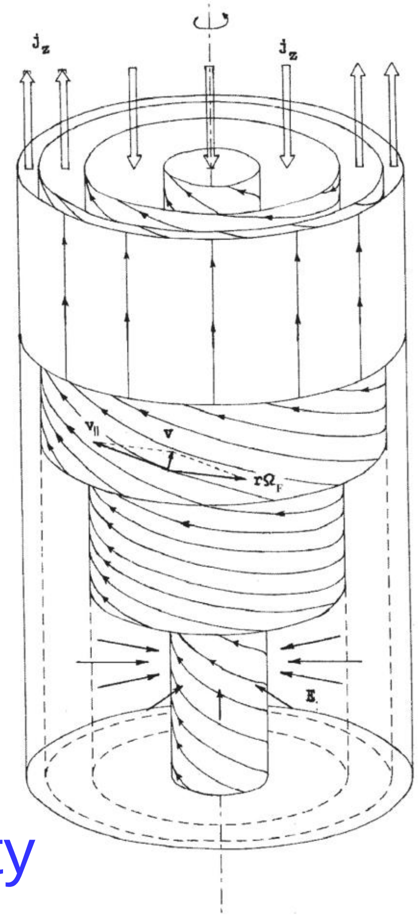
MHD flow + e⁻e⁺ pair creation (at rest)

$$T^{ik} = \left(e + P_s + \frac{\mathbf{b}^2}{4\pi}\right)u^i u^k + \left(P_s + \frac{\mathbf{b}^2}{8\pi}\right)g^{ik}$$
$$+\left[\frac{(P_n - P_s)}{\mathbf{b}^2} - \frac{1}{4\pi}\right]b^i b^k$$

$$\begin{cases} \frac{1}{r^2}\partial_r[r^2(w+b^2)\beta\gamma^2] = R \\ \frac{1}{r^2}\partial_r\{r^2[(w+b^2)\beta^2\gamma^2 + (p+b^2/2)]\} - \frac{2p}{r} = 0 \\ \frac{1}{r}\partial_r[rb\beta\gamma] = 0 \\ \frac{1}{r^2}\partial_r[r^2\rho\beta\gamma] = R \end{cases}$$



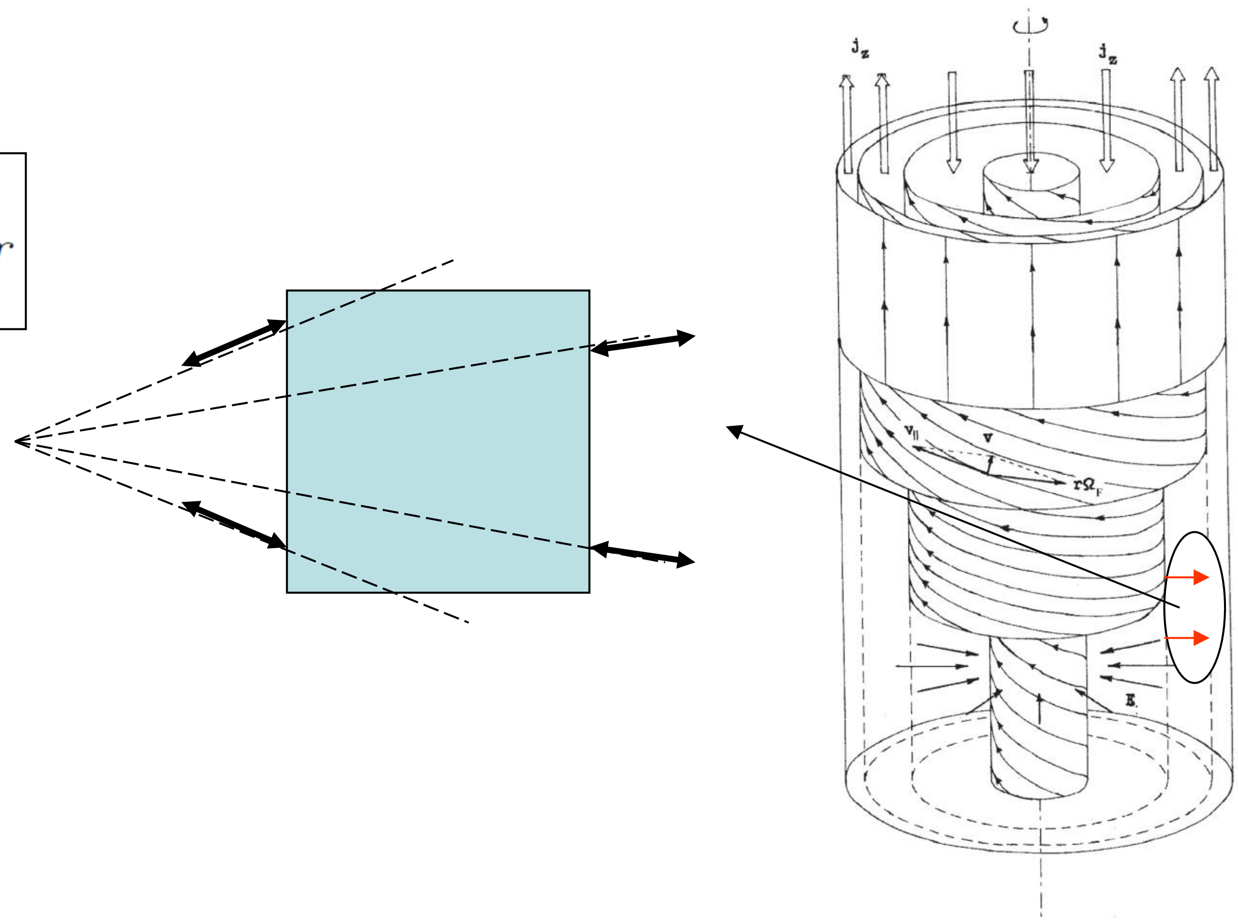
- Anisotropic pressure
- 2D – no equi-potentiality

Loading

Anisotropic pressure

Radial force

$$\mathcal{F} = -\frac{P_s}{r}\mathbf{e}_r$$



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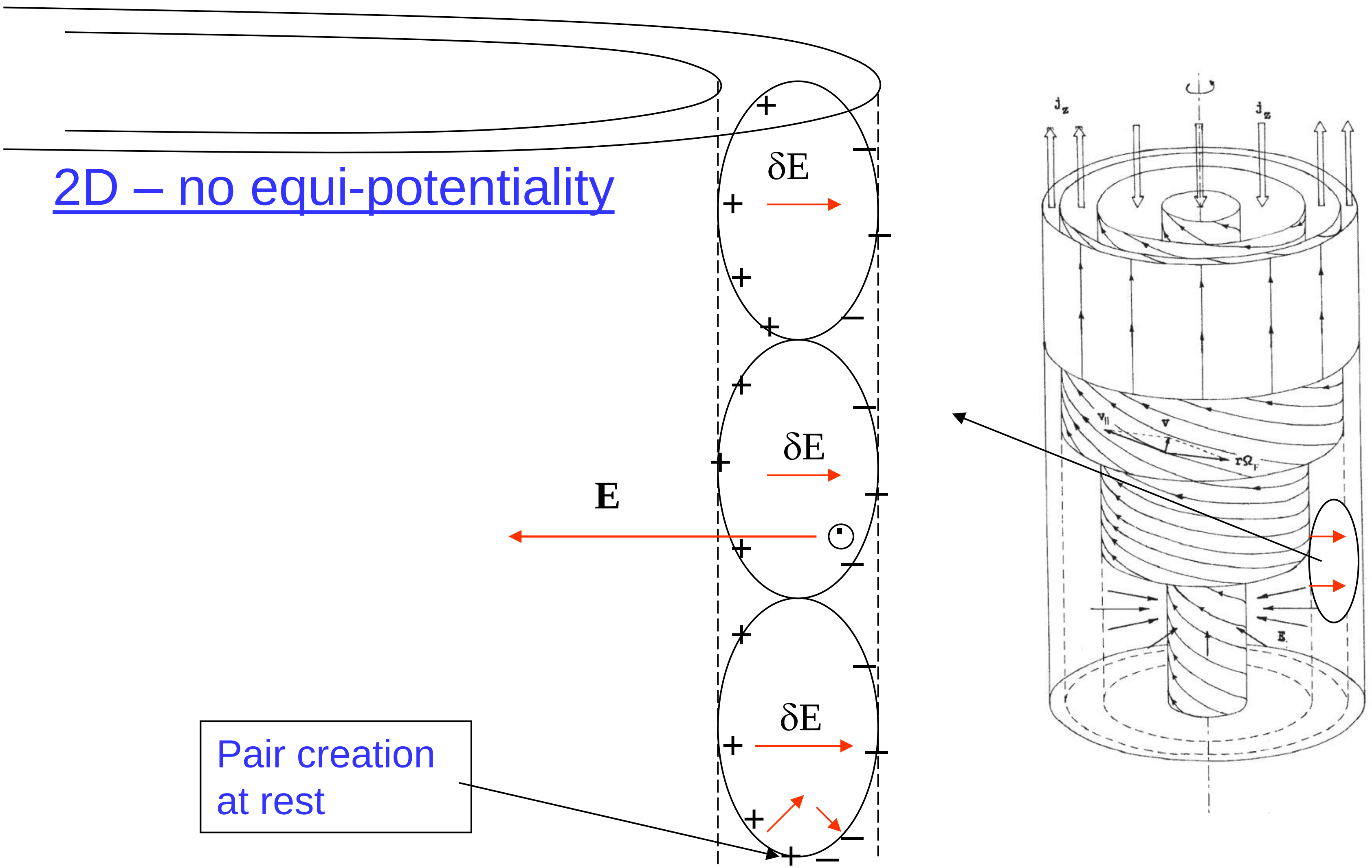

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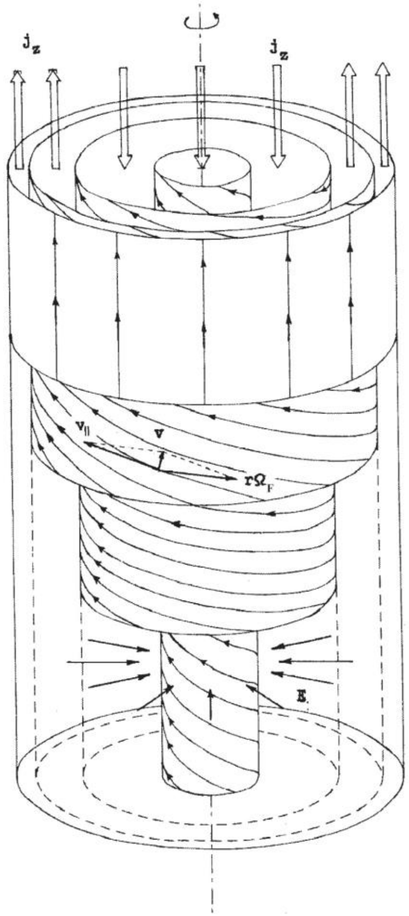
Anisotropic pressure

Rotation in the *rz*-plane

$$T^{ik} = \left(\varepsilon_{\rm ld} + P_s + \frac{\mathbf{b}^2}{4\pi}\right) U^i U^k + \left(P_s + \frac{\mathbf{b}^2}{8\pi}\right) g^{ik} - \left(\frac{P_s}{\mathbf{b}^2} + \frac{1}{4\pi}\right) b^i b^k .$$

$$\varepsilon_{\rm ld} = n_{\rm ld}^{\rm com} m_{\rm e} c^2 \Gamma,$$

$$P_s = \frac{1}{2} n_{\rm ld}^{\rm com} m_{\rm e} c^2 \Gamma$$



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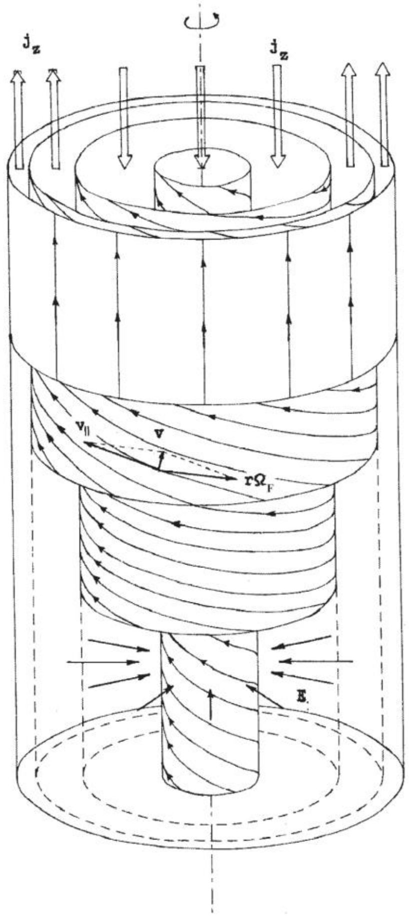
Anisotropic pressure

Full system of equation was known

E.Asseo & D.Beaufils. Ap&SS, **89**, 133 (1983)
R.Lovelace et al. ApJS, **62**, 1 (1986)
E.Tsikarisvili, A.Rogava, D.Tsikauri. ApJ, **439**, 822 (1992)
I.Kuznetsova, ApJ, **618**, 432 (2005)

$$\begin{cases} E(\Psi) = \dfrac{\Omega_{\rm F} I}{2\pi}(1+|\beta|) + \mu_{\rm ld}\eta_{\rm ld} < \gamma > + \mu\eta < \gamma >, \\ L(\Psi) = \dfrac{I}{2\pi}(1+|\beta|) + \mu_{\rm ld}\eta_{\rm ld}\varpi u_{\varphi} + \mu\eta\varpi u_{\varphi}. \end{cases}$$

$$\begin{cases} \dfrac{I}{2\pi} = \dfrac{\alpha^2 L - (\Omega_F - \omega)\varpi^2(E - \omega L)}{\left[\alpha^2 - (\Omega_F - \omega)^2\varpi^2\right](1-\beta) - M^2}, \\ \gamma = \dfrac{1}{\alpha\mu\eta}\dfrac{\alpha^2(E - \Omega_F L)(1-\beta) - M^2(E - \omega L)}{\alpha^2 - (\Omega_F - \omega)^2\varpi^2(1-\beta) - M^2}, \\ u_{\hat\varphi} = \dfrac{1}{\varpi\mu\eta}\dfrac{(E - \Omega_F L)(\Omega_F - \omega)\varpi^2(1-\beta) - LM^2}{\left[\alpha^2 - (\Omega_F - \omega)^2\varpi^2\right](1-\beta) - M^2} \end{cases}$$



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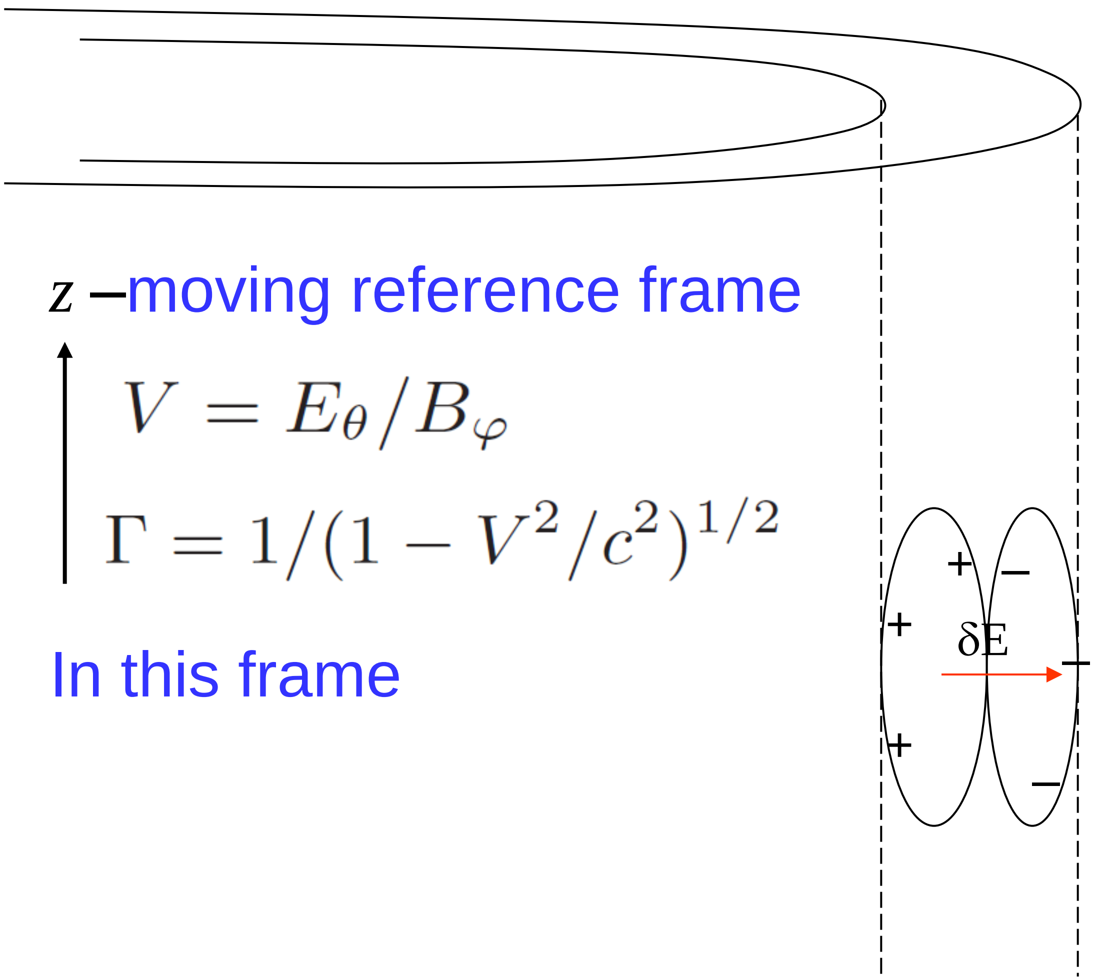
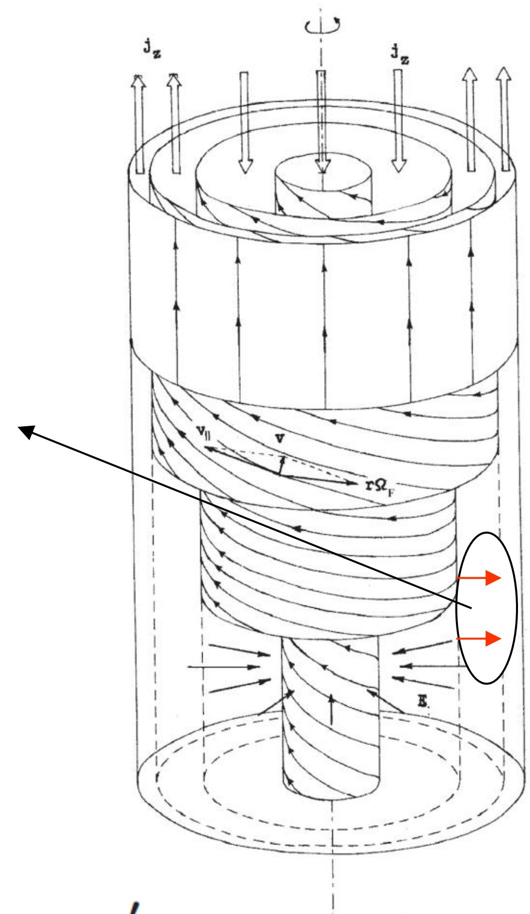


z –moving reference frame

$$V = E_\theta / B_\varphi$$

$$\Gamma = 1/(1 - V^2/c^2)^{1/2}$$

In this frame



$$\mathbf{p}' = p'_{||}\mathbf{b} + p'_{\perp}\cos\omega t'\mathbf{n}_1 + p'_{\perp}\sin\omega t'\mathbf{n}_2$$

Loading

Particle motion (laboratory frame)

$$\begin{aligned} p_r &= mcu_r = mV\Gamma \sin\alpha \cos\alpha (1 - \cos\omega t'), \\ p_\phi &= mcu_\phi = mV\Gamma \cos\alpha \sin\omega t', \\ p_z &= mcu_z = mV\Gamma^2 \cos^2\alpha (1 - \cos\omega t'). \end{aligned}$$

$$\mathcal{E} = mc^2\Gamma^2 \left[1 - V^2/c^2 (\sin^2\alpha + \cos^2\alpha \cos\omega t')\right]$$

Averaging procedure

$$< A >_t = \frac{1}{T} \int_0^{T'} A(t') \frac{\mathrm{d}t}{\mathrm{d}t'} \mathrm{d}t' = < A(t') \frac{T'}{T} \frac{\mathrm{d}t}{\mathrm{d}t'} >_{t'}$$

Loading

Hydrodynamical motion

$$
\begin{aligned}
< v_r >_t &= \frac{V\Gamma^{-1} \sin\alpha \cos\alpha}{1 - V^2/c^2 \sin^2\alpha}, \\
< v_\phi >_t &= 0, \\
< v_z >_t &= \frac{V \cos^2\alpha}{1 - V^2/c^2 \sin^2\alpha}
\end{aligned}
$$

$$
\gamma_{\rm hd} = \Gamma\sqrt{1 - V^2/c^2 \sin^2\alpha}
$$

Mean energy

$$
< \gamma >_t = \Gamma^2 \left(1 - \frac{V^2}{c^2} \sin^2\alpha\right) \left[1 + \frac{1}{2} \frac{\cos^4\alpha}{(1 - V^2/c^2 \sin^2\alpha)^2}\right]
$$

$$
< \gamma >_t \approx \frac{3}{2}\gamma_{\rm hd}^2
$$

Loading

Hydrodynamical motion

$$E(\Psi) = \frac{\Omega_{\rm F} I}{2\pi}(1 + |\beta|) + \mu_{\rm ld}\eta_{\rm ld} < \gamma > + \mu\eta < \gamma >,$$

$$L(\Psi) = \frac{I}{2\pi}(1 + |\beta|) + \mu_{\rm ld}\eta_{\rm ld}\varpi u_\varphi + \mu\eta\varpi u_\varphi.$$

$$\mu = \varepsilon/n = mc^2$$

$$\mu_{\rm ld} = \varepsilon_{\rm ld}/n_{\rm ld} = mc^2 < \gamma >$$

$$\beta = 4\pi \frac{\cancel{P_n} - P_s}{h^2}$$

Loading

Critical number density

$$\frac{1}{\Gamma^2} = \frac{1}{x_r^2} + \frac{B_\varphi^2 - \mathbf{E}^2}{B_\varphi^2}$$

- Direct calculation of the field disturbances in
- Loading pressure $|\beta| \sim 1$
- Electric field disrurbance $\delta\boldsymbol{E} \sim \boldsymbol{E}$
- Anisotropic pressure force δF~ $\boldsymbol{F}$

$$\frac{1}{\alpha}\nabla_k\left[\frac{1}{\alpha\varpi^2}A\nabla^k\Psi\right] + \frac{(\Omega_F-\omega)}{\alpha^2}(1-\beta)\frac{d\Omega_F}{d\Psi}(\nabla\Psi)^2$$
$$+\frac{64\pi^4}{\alpha^2}\varpi^2\frac{1}{2M^2}\frac{\partial}{\partial\Psi}\left(\frac{G}{A}\right) - 8\pi^3\mu n\frac{1}{\eta}\frac{d\eta}{d\Psi}$$
$$-\cancel{8\pi^3 P_n\frac{1}{s_1}\frac{ds_1}{d\Psi}} - 16\pi^3 P_s\frac{1}{s_2}\frac{ds_2}{d\Psi} = 0.$$

I.Kuznetsova

Loading

Critical number density

- Direct calculation of the field disturbances in
- Loading pressure $|\beta| \sim 1$
- Electric field disrurbance $\delta \boldsymbol{E} \sim \boldsymbol{E}$
- Anisotropic pressure force $\delta \mathrm{F} \sim \boldsymbol{F}$

$$\frac{1}{\Gamma^2} = \frac{1}{x_r^2} + \frac{B_\varphi^2 - \mathbf{E}^2}{B_\varphi^2}$$

$$n_{\rm cr} = \frac{B_\varphi^2}{m_{\rm e} c^2 \Gamma^2}$$

A problem

Longitudinal electric field

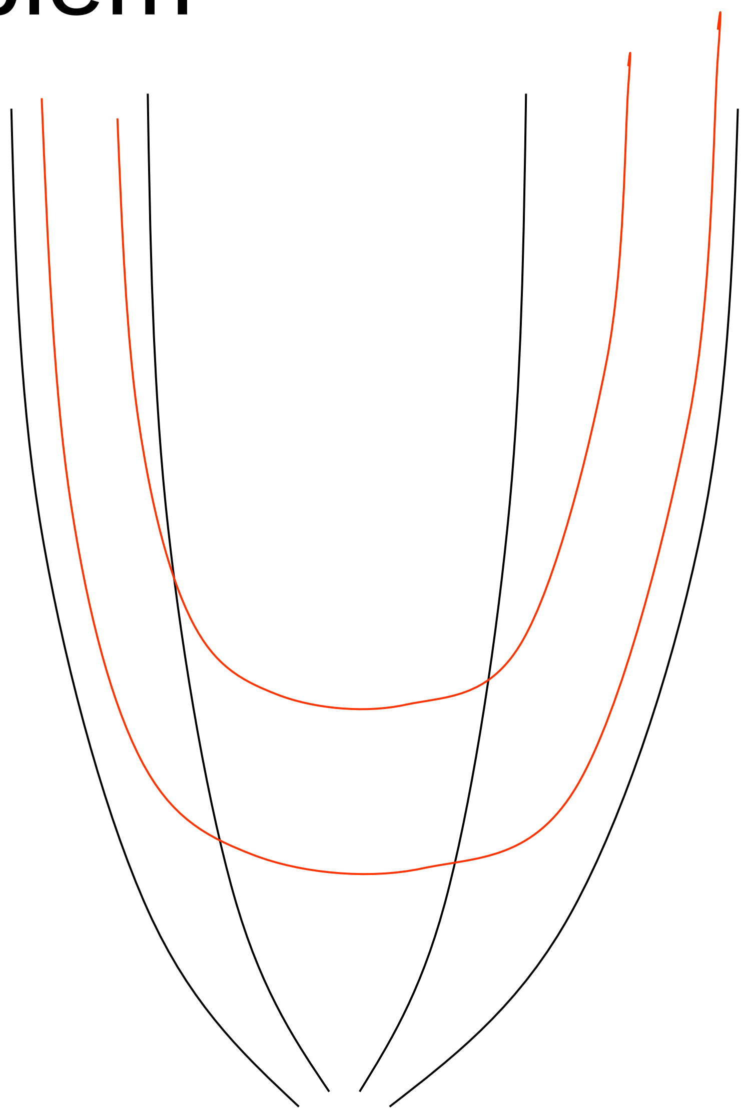
Magnetically dominated wind → Any disturbance → Longitudinal electric field

$$\mathrm{E}_{\perp} \longrightarrow E_{\|}$$

A problem

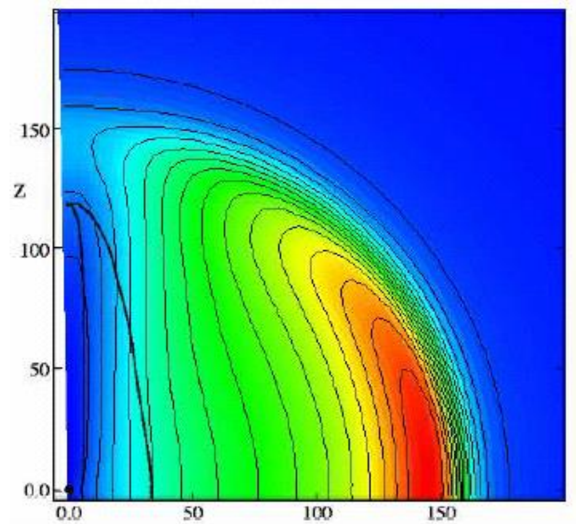
<u>Longitudinal electric field</u>

It is impossible to switch on the disturbance without generating the longitudinal electric field.



A problem

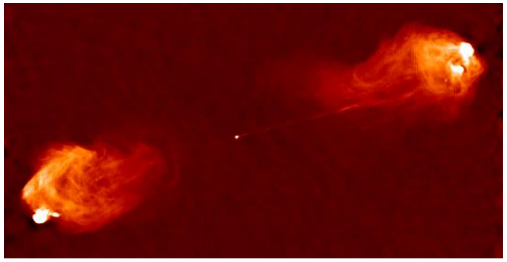
If there is no external environment, one can prolong the solution up to infinity.



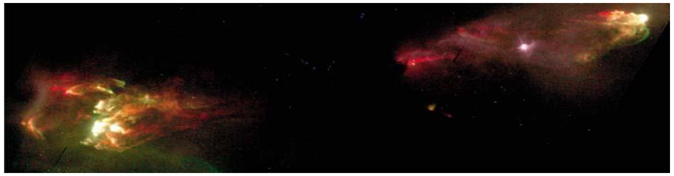
S.Komissarov, MNRAS,**350**, 1431 (2004)

But what to do if the wind meets the ambient?

Lobes in AGN



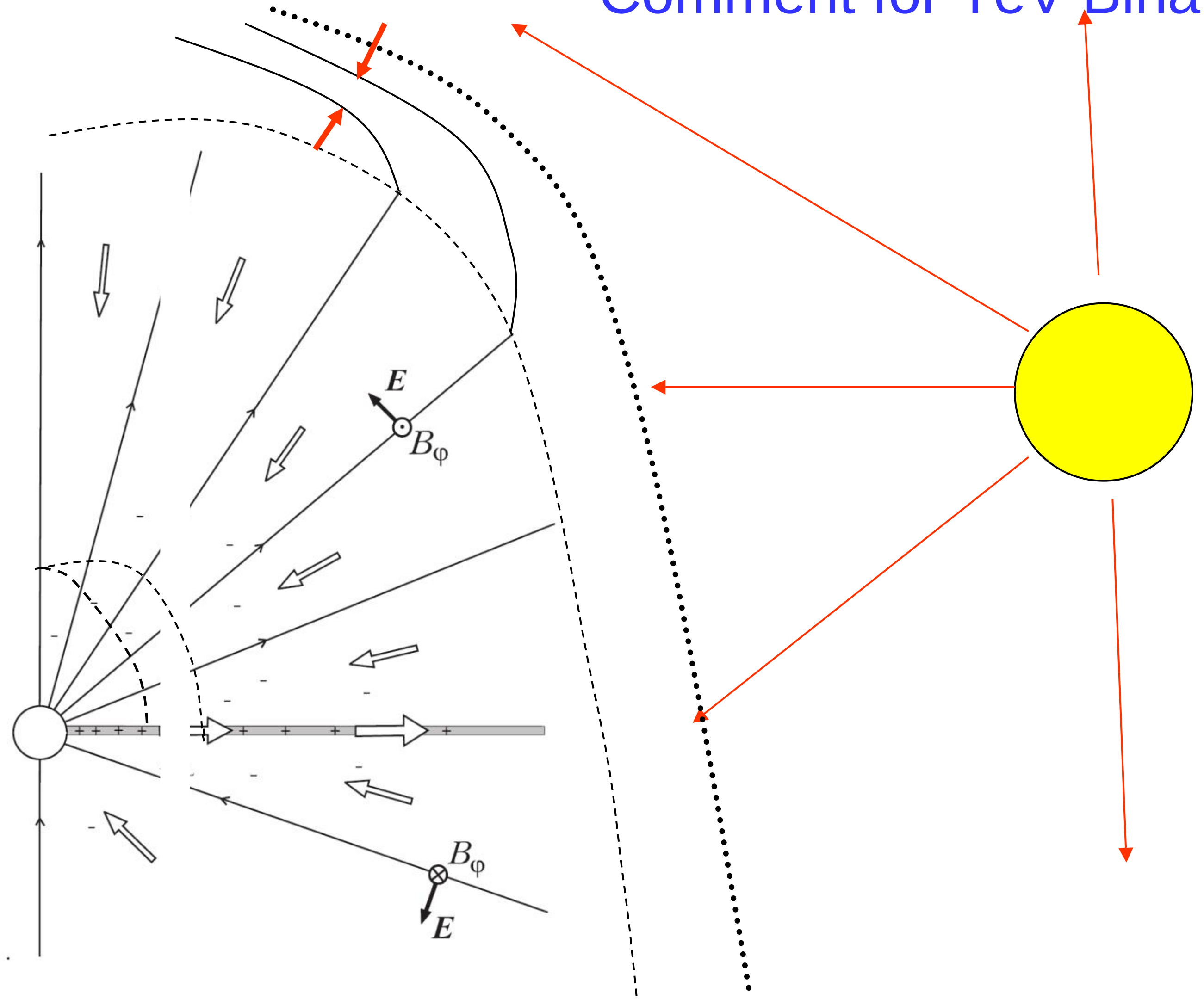
HH objects in YSOs



Stellar wind in binaries

A problem

Comment for TeV Binaries



Conclusion

1. Radiation drag might be a reason for deceleration.
2. Real physical conditions are not known.
3. PIC is necessary.

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THANKS AGAIN!