On the Deceleration of Relativistic Jets in Active Galactic Nuclei

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P.N.Lebedev Physical Institute

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with

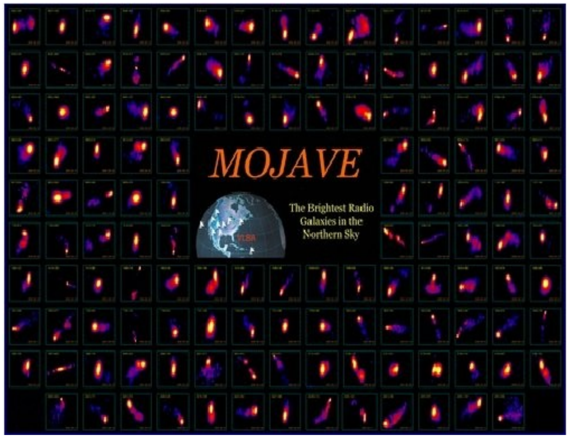
A.V.Chernoglazov, E.E. Nokhrina, N.Zakamska

Plan

- Thanks
- AGN Jets – internal structure (observations)
- AGN Jets – internal structure (theory)
- Possible mechanism(s) of deceleration
- Thanks again

Internal structure – AGN

New possibilities

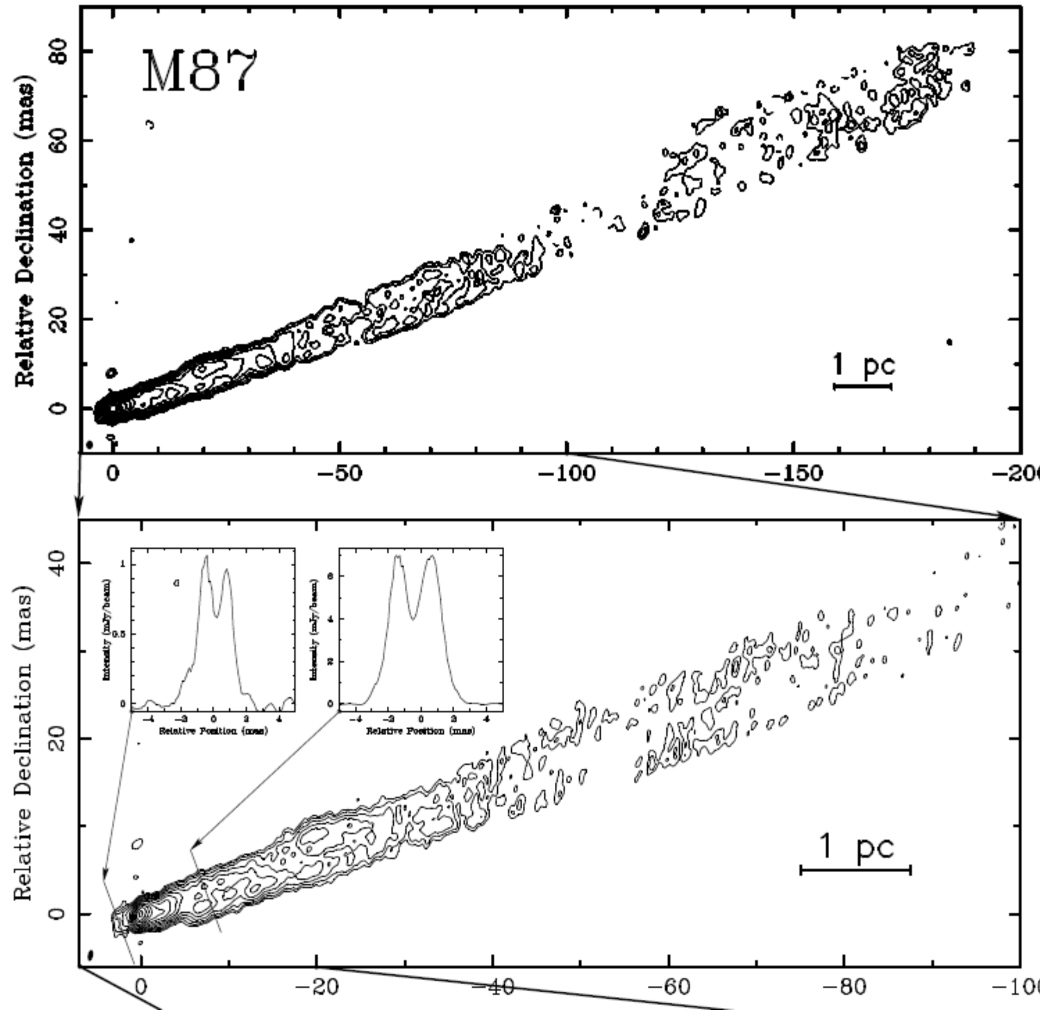


MOJAVE team (time)

Radioastron (base)

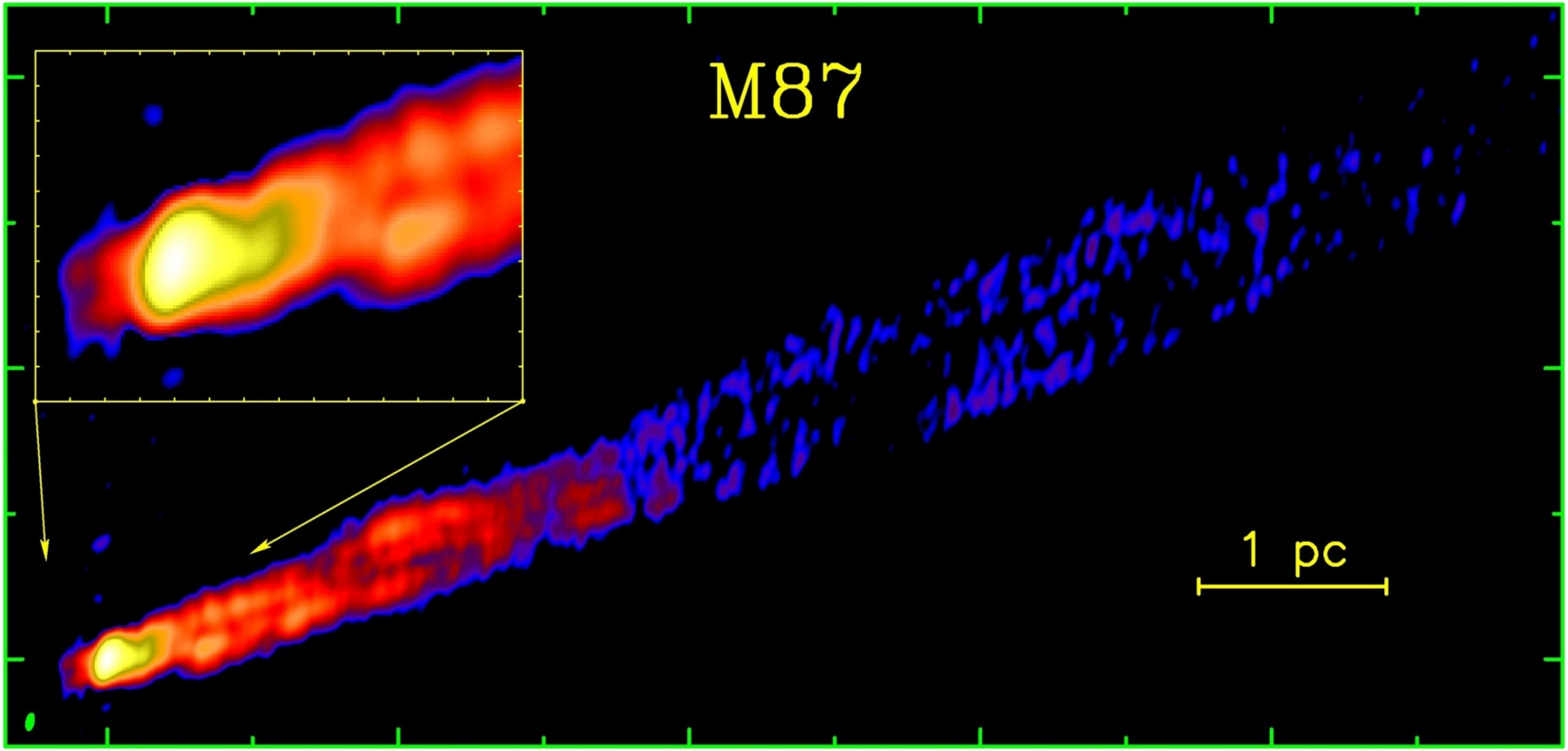
Internal structure – AGN

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



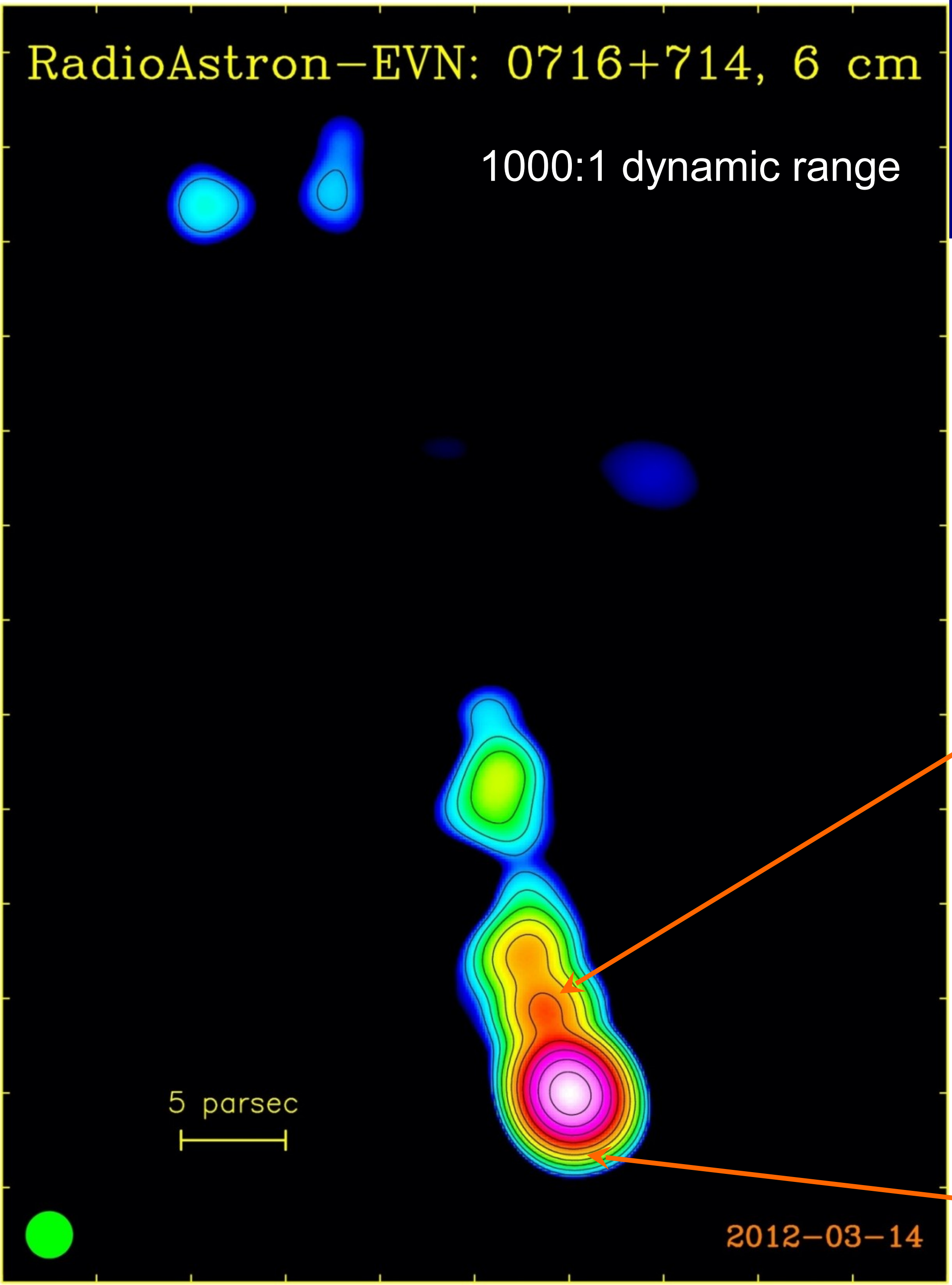
VLBA+VLA1, 15 GHz

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

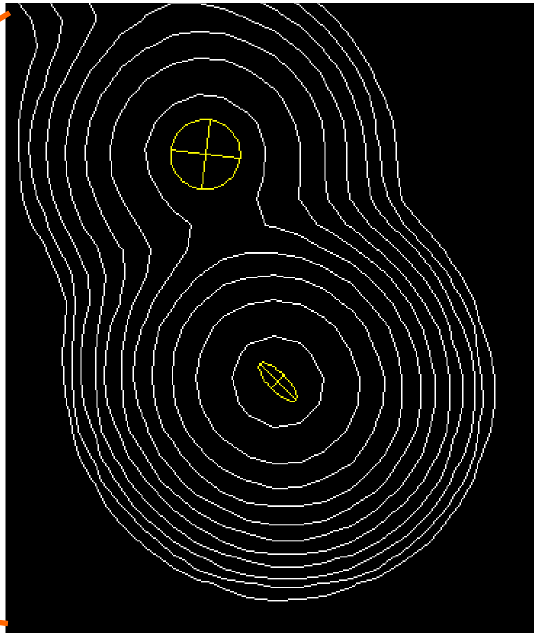


Y.Y.Kovalev et al, ApJ, **668**, L27 (2007)

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).

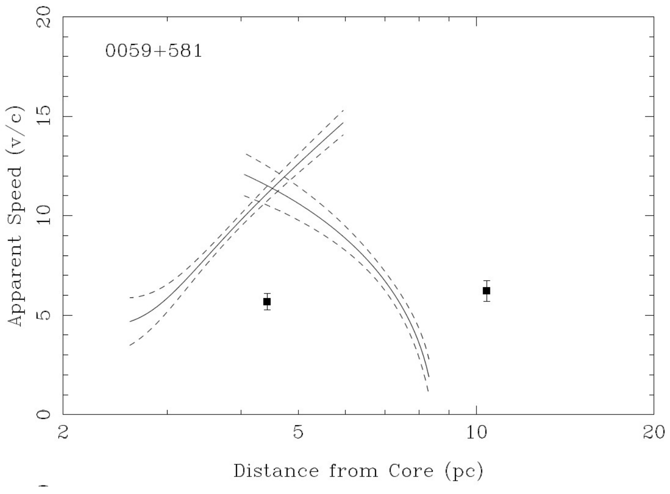


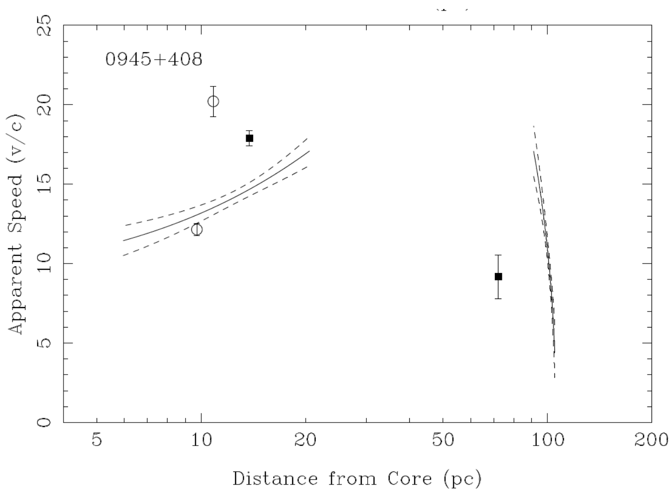
Internal structure – AGN

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

Acceleration at small distances,
decceleration at large distances.

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





Internal structure – AGN

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

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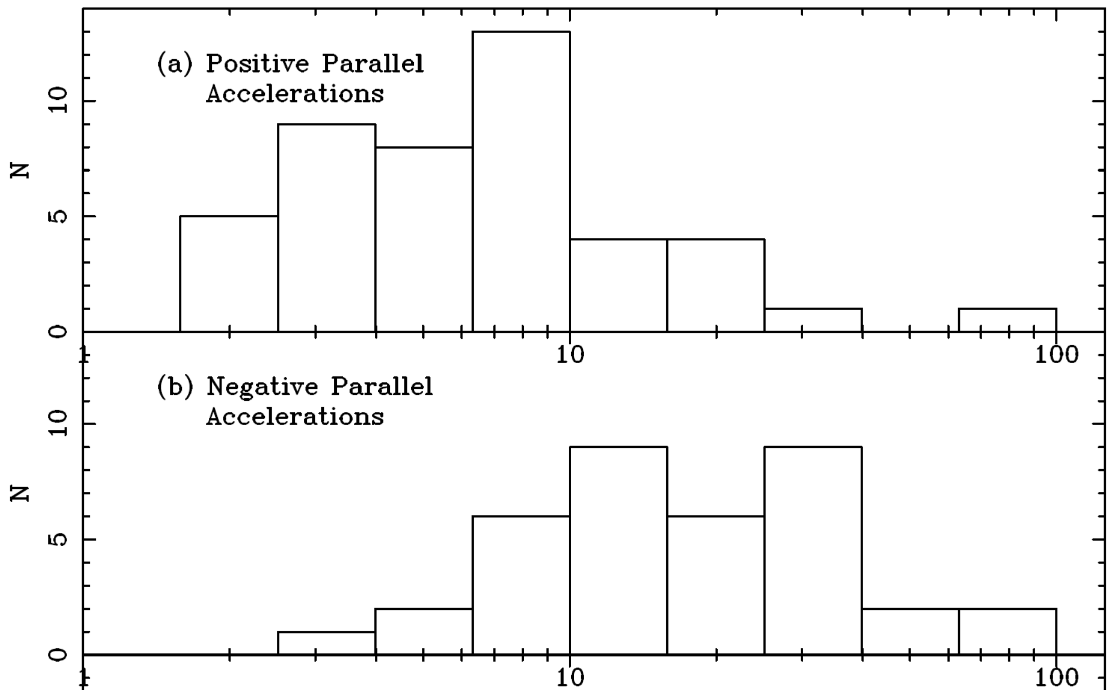


pc (projection)

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)

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

μ now

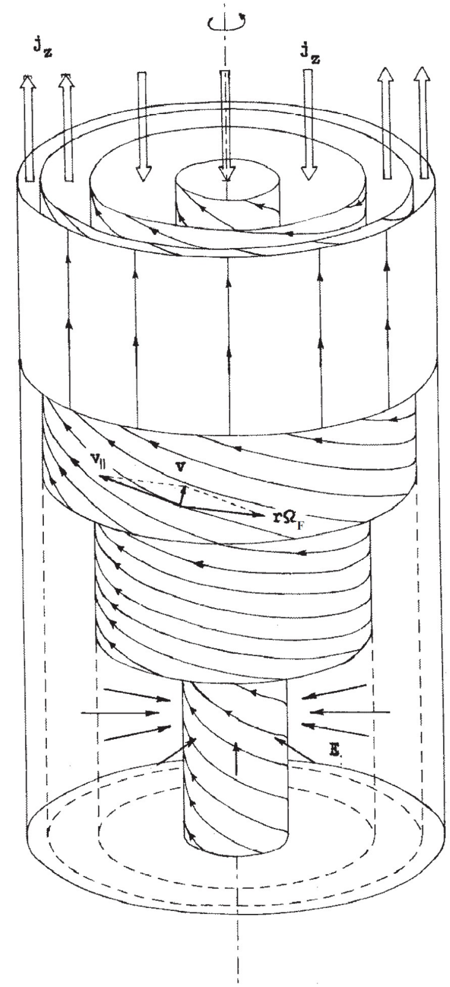
- Multiplicity parameter

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

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

- Total potential drop

$$\lambda\sigma_{\rm M} \sim \frac{eE_r r_{\rm jet}}{m_{\rm e} c^2}$$

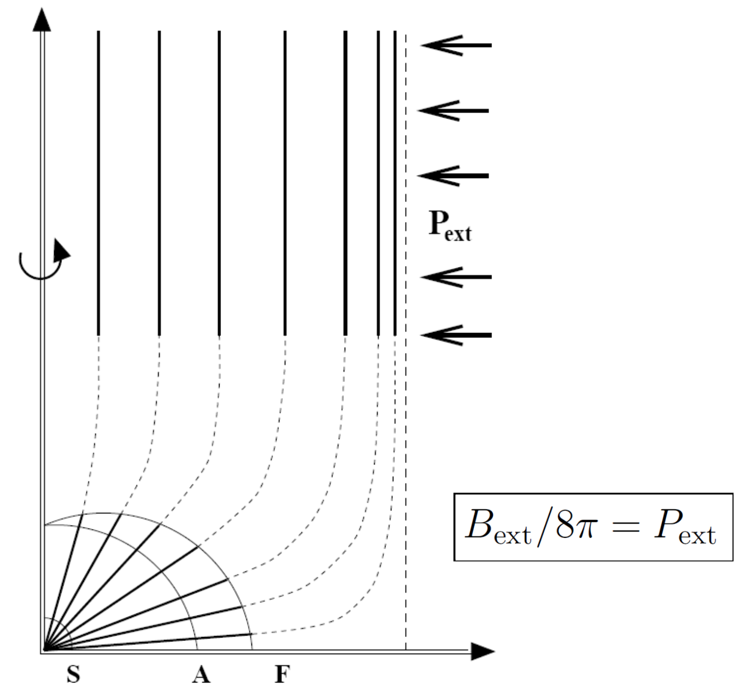


Jets – theory

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

1D approach for cylindrical jets

$$\left\{\begin{aligned} \frac{\mathrm{d}\mathcal{M}^2}{\mathrm{d}r_\perp} &= F_1(\mathcal{M}^2, \Psi, r_\perp) \\ \frac{\mathrm{d}\Psi}{\mathrm{d}r_\perp} &= F_2(\mathcal{M}^2, \Psi, r_\perp) \end{aligned}\right.$$



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

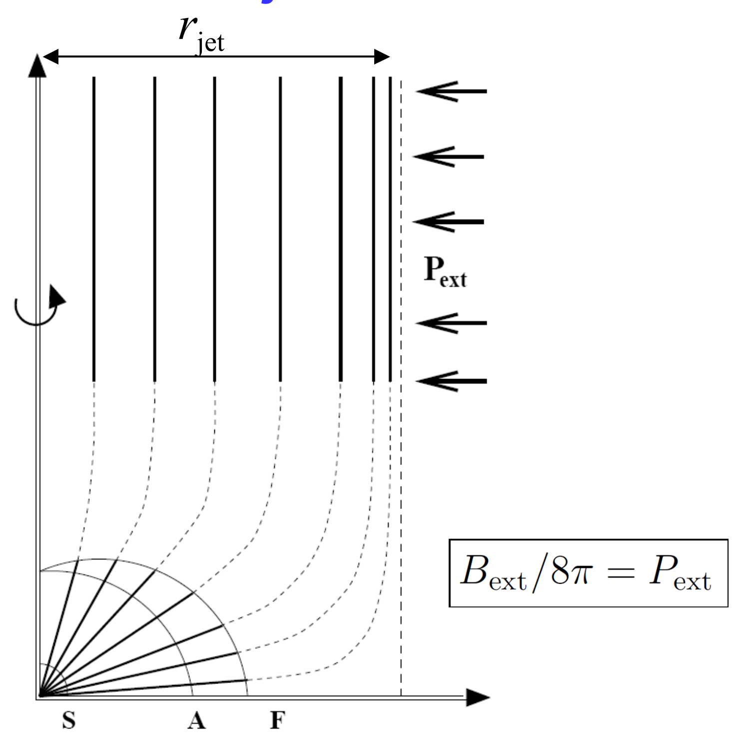
T.Lery, J.Heyvaerts, S.Appl, C.A.Norman. A&A, **347**, 1055 (1999)

Jets – theory

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

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

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



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)

Jets – theory

Simple asymptotic solutions for Lorentz-factor

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

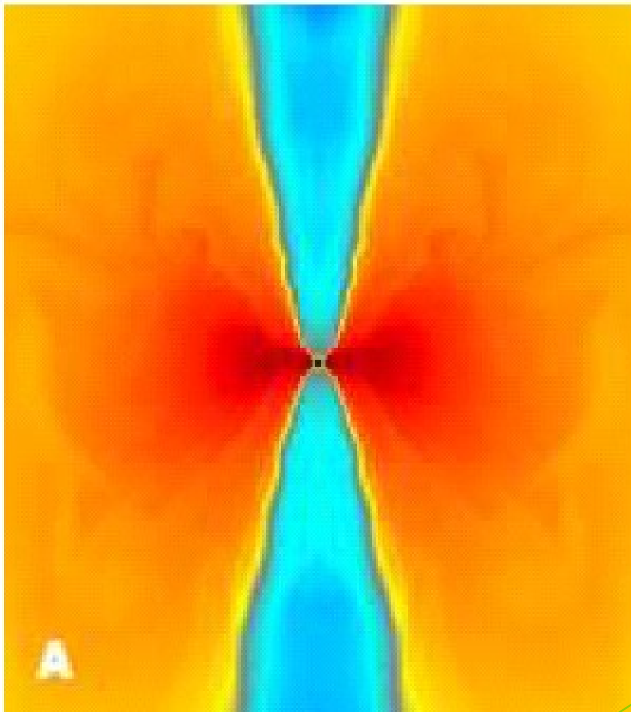
$$\boxed{\Gamma = x_r} \qquad x_r = \Omega_F r_\perp / c$$

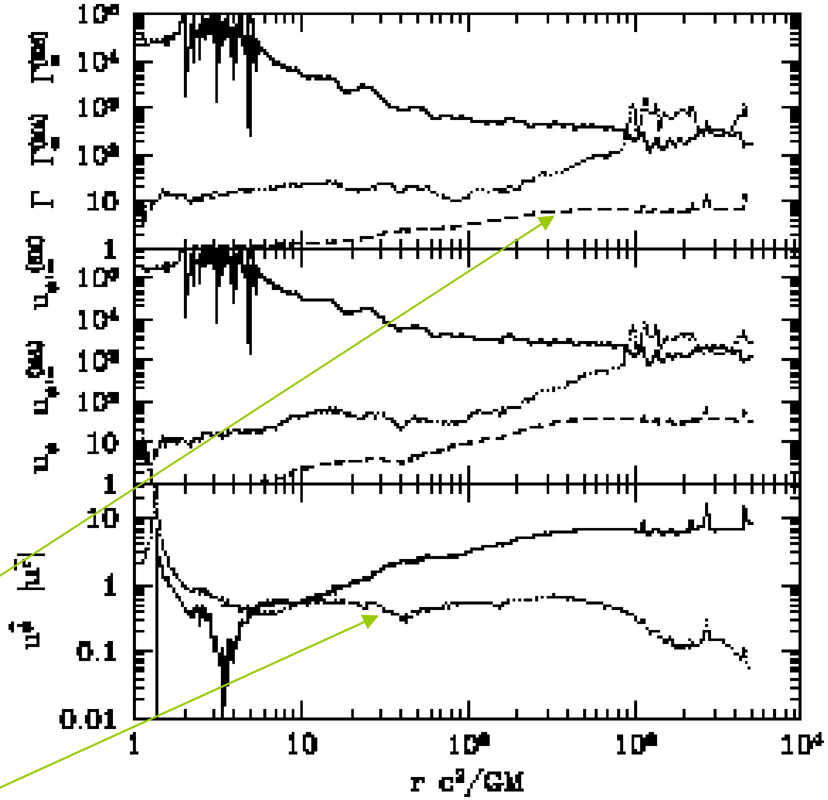
Quasi-radial flows

$$\boxed{\Gamma = C\sqrt{\frac{R_c}{r_\perp}}}$$

Jets – theory

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





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

Jets – theory

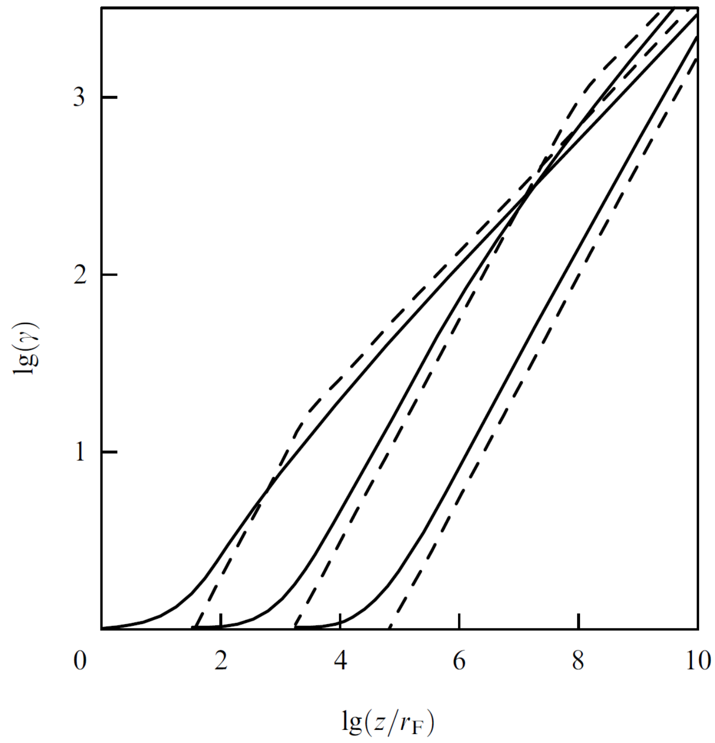
Parabolic structure terminates the efficiency of acceleration

- 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* $k = 2$

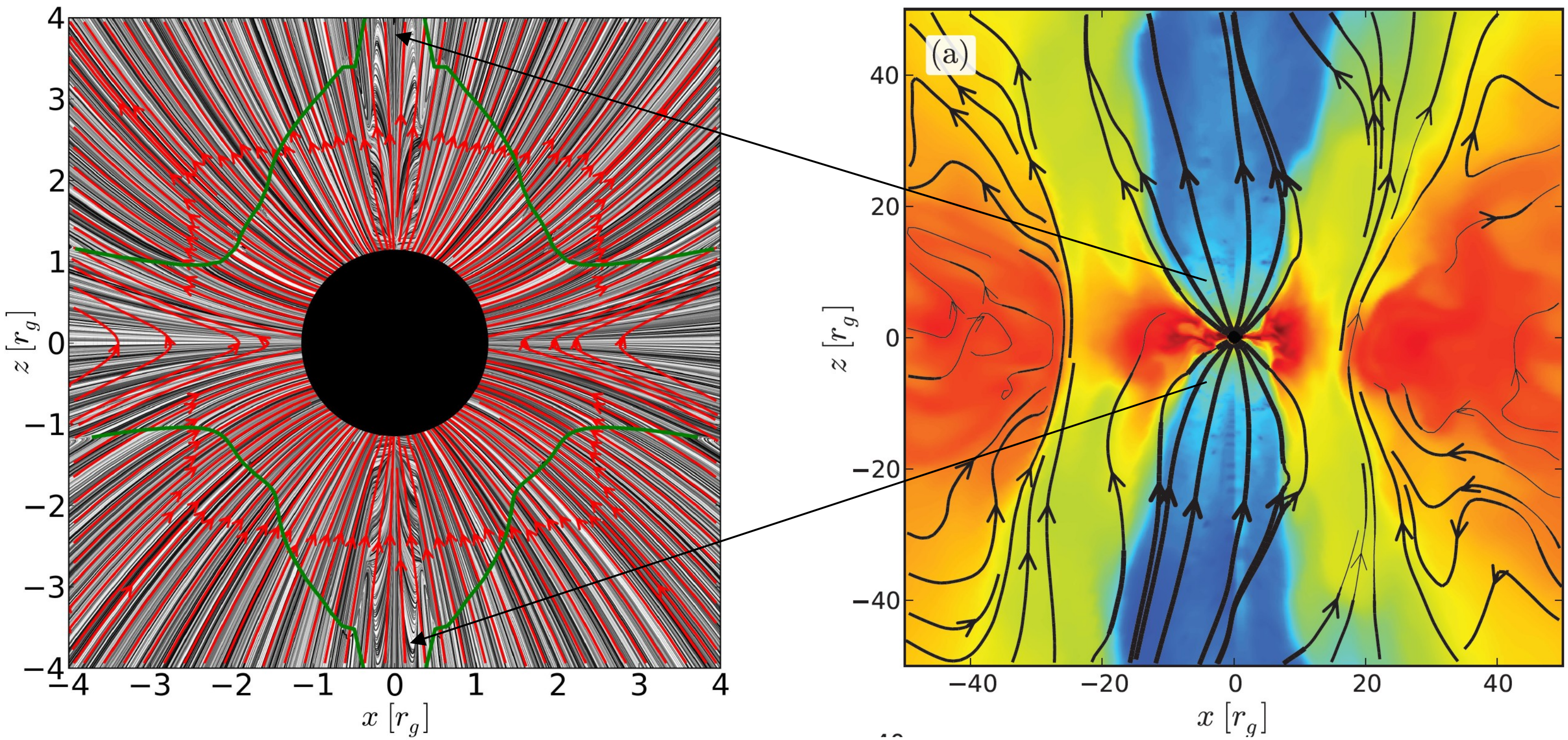


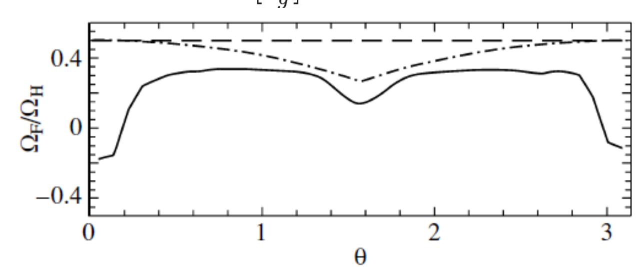
R. Narayan, J.McKinney, A.F.Farmer, MNRAS, **375**, 548, 2006

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

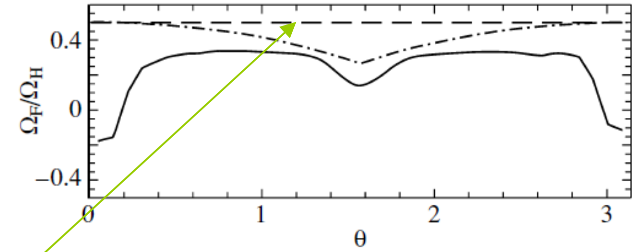
J.C.McKinney, A.Tchekhovskoy, R.D.Blandford. MNRAS, **423**, 3083 (2012)

Parabolic?





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

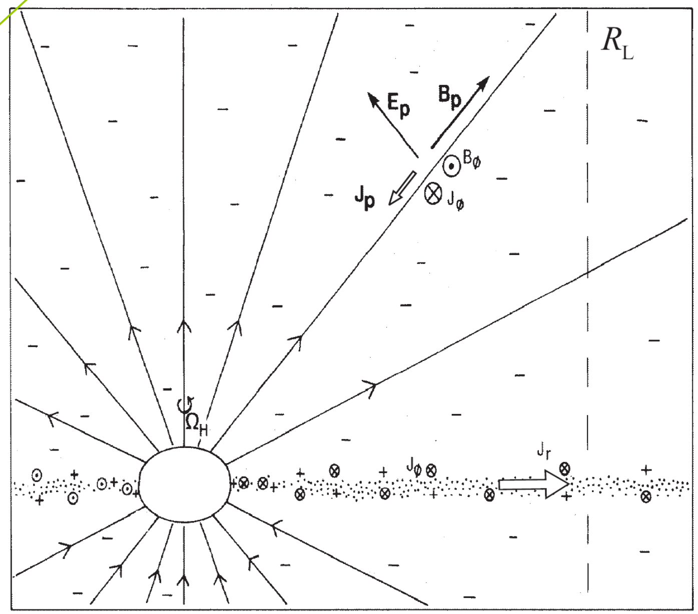


Monopole + Monopole

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

Horizon 'boundary condition'

$$4\pi I(\theta) = [\Omega_H - \Omega_F(\theta)]\Psi_0 \sin^2\theta.$$



At large distances

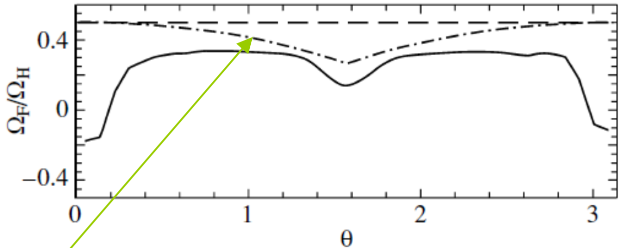
$$4\pi I(\theta) = \Omega_F(\theta)\Psi_0 \sin^2\theta.$$

Then

$$\Omega_F = \frac{\Omega_H}{2}, \qquad I(\Psi) = I_M = \frac{\Omega_F}{4\pi}\left(2\Psi - \frac{\Psi^2}{\Psi_0}\right).$$

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

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

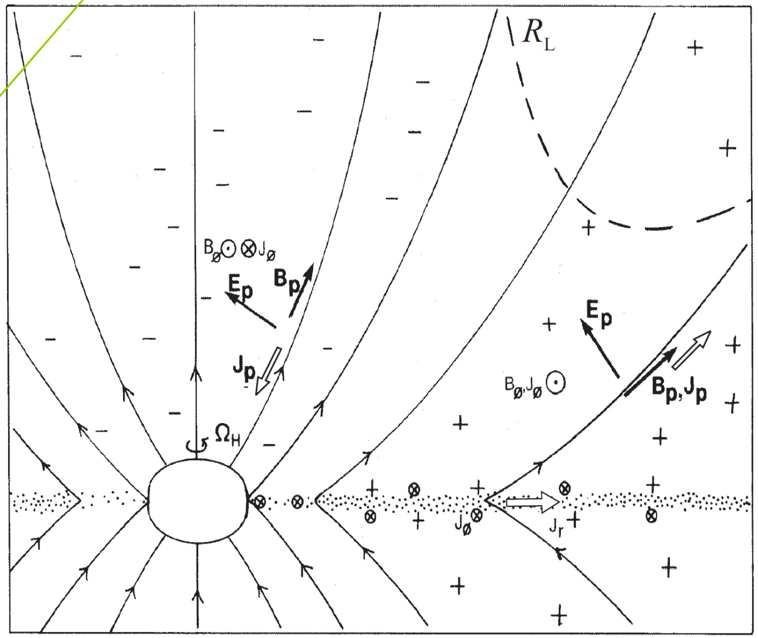


Parabolic + Parabolic

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

Horizon 'boundary condition'

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



At large distances

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

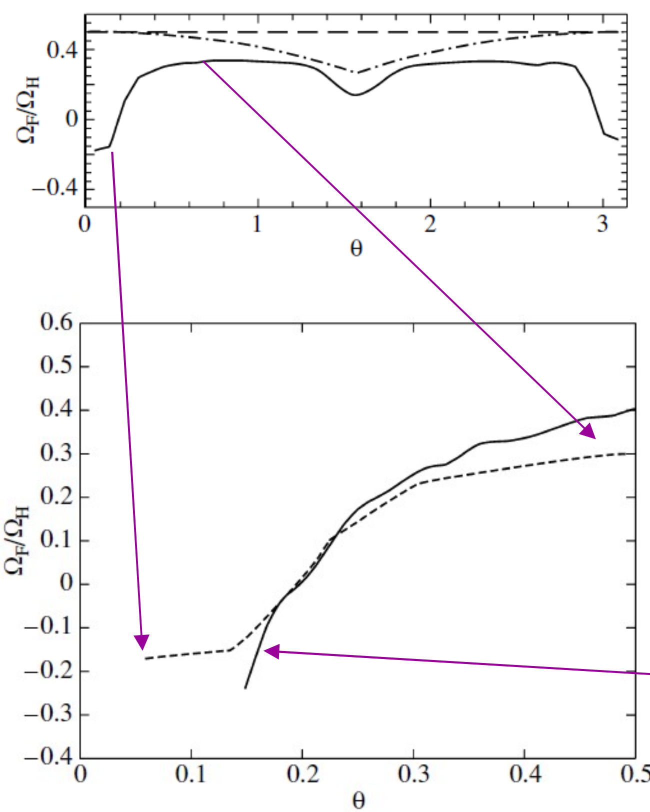
Then

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

Excellent agreement with analytical force-free behaveour

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

Monopole + Cylinder



$$\begin{cases} A_1(\Psi) = \varpi^2 B_z \\ A_2(\Psi) = c^2 \int\limits_0^{\varpi} x^2 \frac{d}{dx} (B_z)^2 \, dx \\ A_3(\Psi) = \frac{1}{2\pi} \sin\theta \frac{r_g^2 + a^2}{r_g^2 + a^2 \cos^2\theta} \left(\frac{d\Psi}{d\theta}\right) \end{cases}$$

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

Jets – theory

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)

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

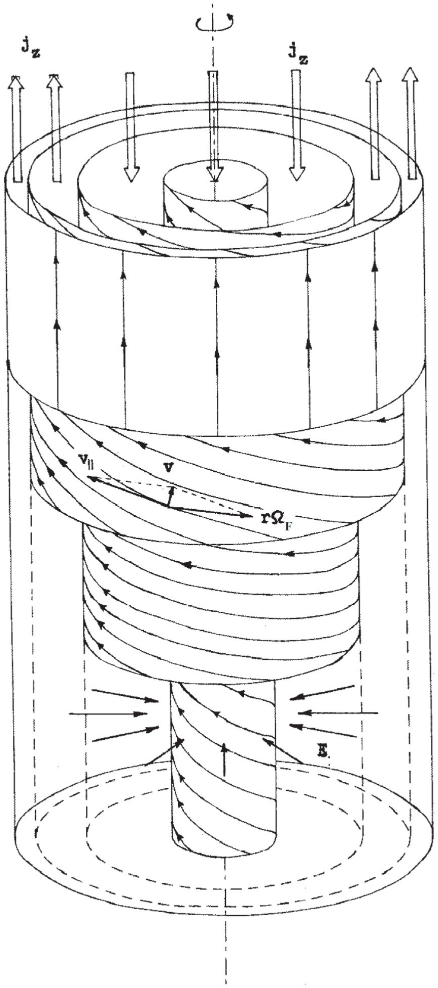
$$r_{\mathrm{core}} = \gamma_{\mathrm{in}} R_{\mathrm{L}}$$

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

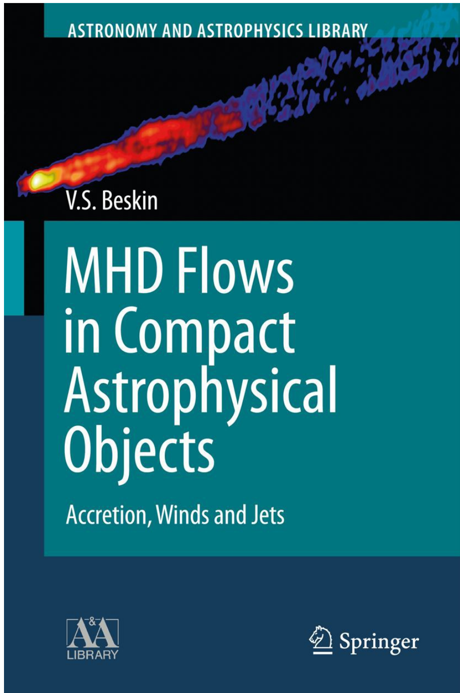
Theorem 5.2. *In the relativistic case, in the presence of the environment with rather high pressure* ($B_{\rm ext} > B_{\rm min}$) *the poloidal magnetic field inside the jet remains practically constant:* $B_{\rm p} \approx B_{\rm ext}$. *For small external pressure* ($B_{\rm ext} < B_{\rm min}$) *in 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*

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

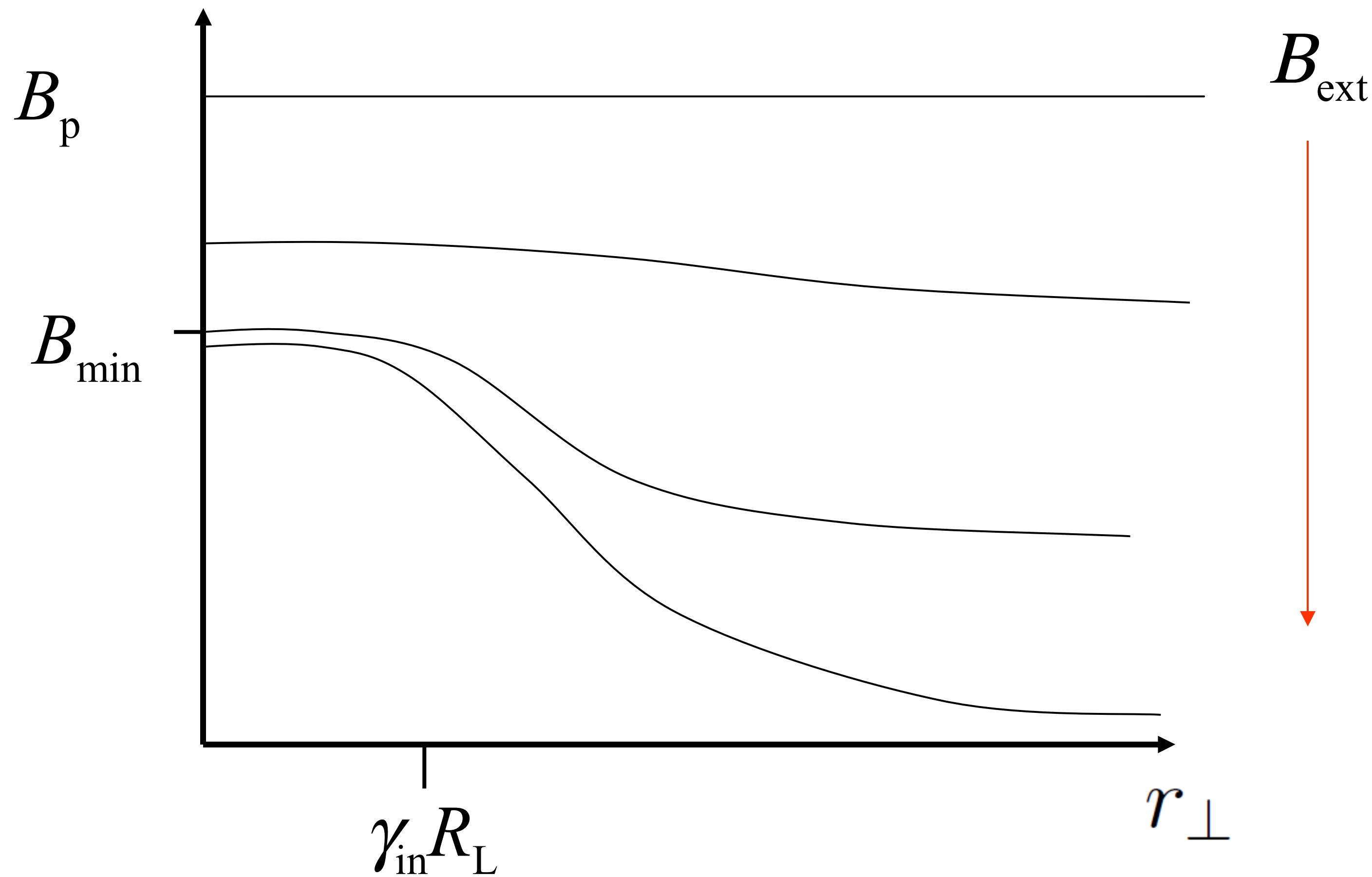
where $\alpha < 2$.



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

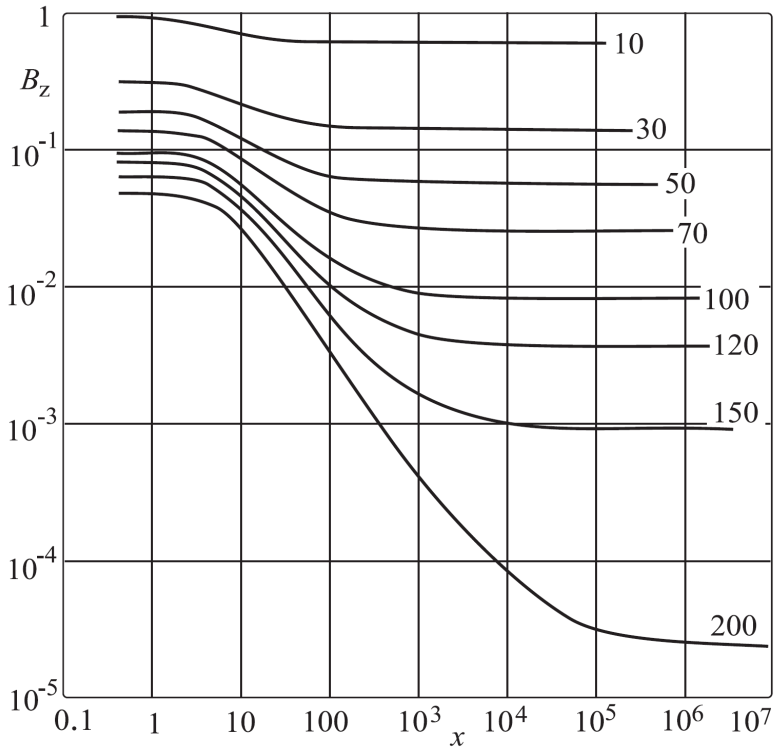
Central core

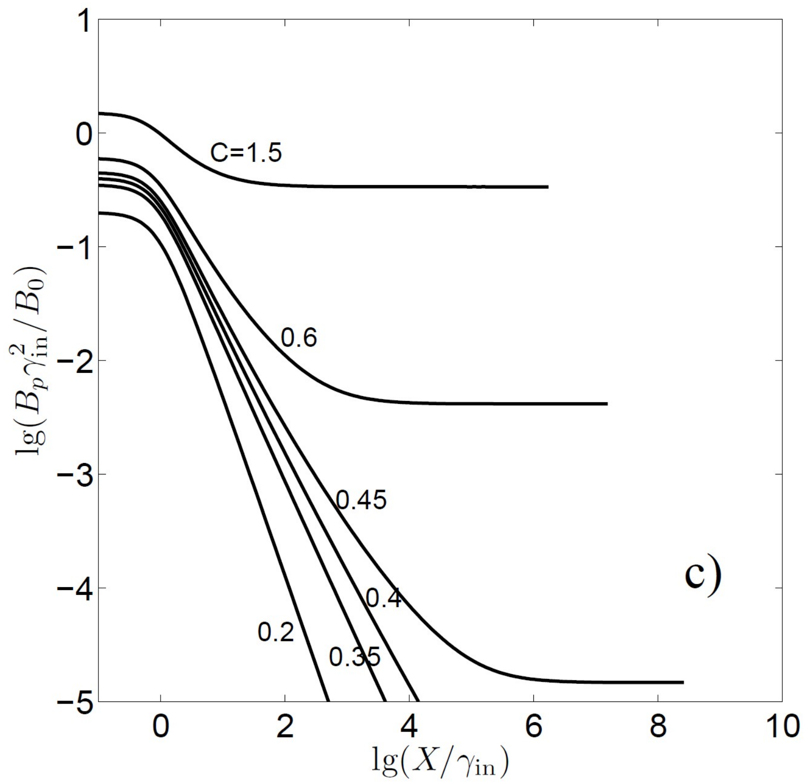
$$B_{\rm min} = \frac{1}{\sigma_{\rm M}\gamma_{\rm in}} B(R_{\rm L}) \qquad r_{\rm core} = \gamma_{\rm in} R_{\rm L}$$



Central core

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



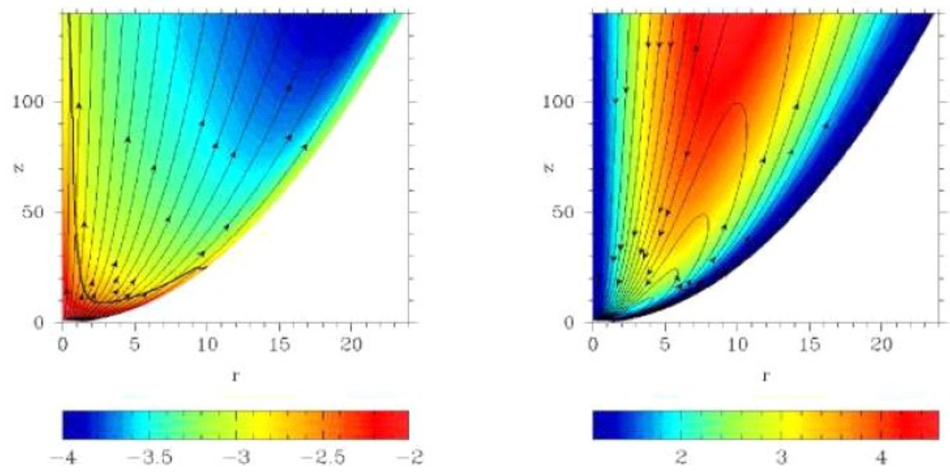


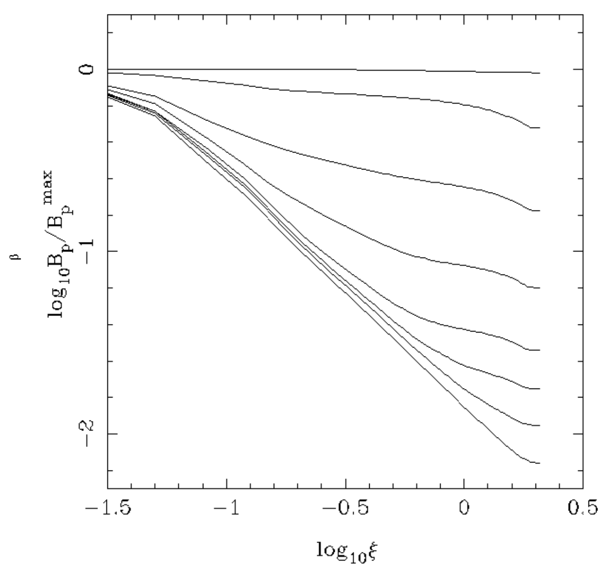
VB, E.E.Nokhrina.
MNRAS, **389**, 335 (2007)
MNRAS, **397**, 1486 (2009)

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

Central core

S. S. Komissarov et al.

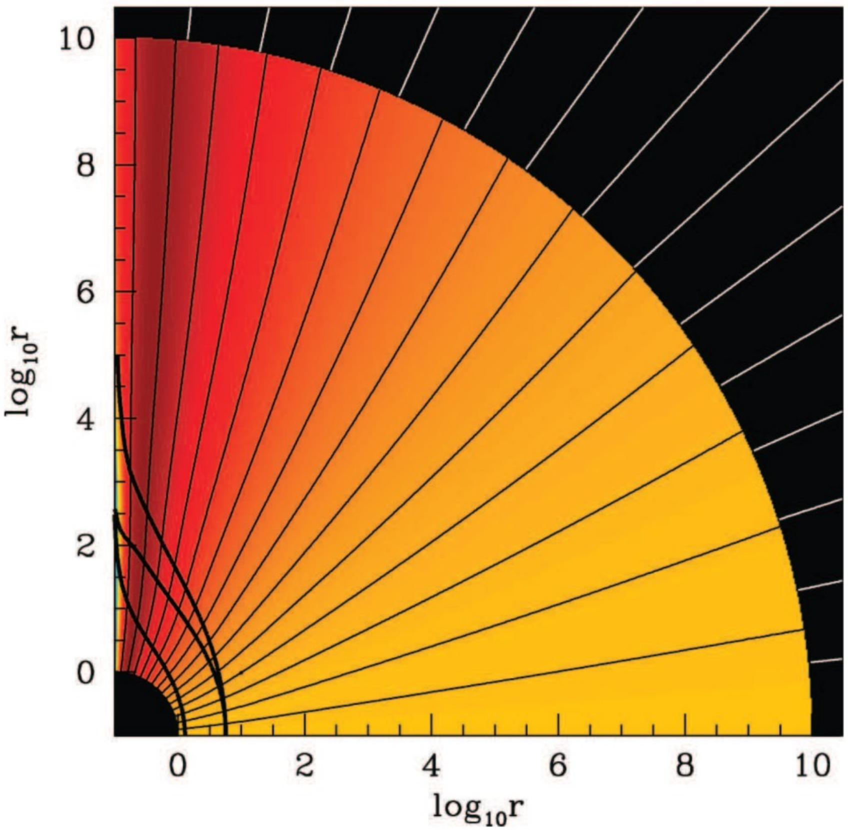


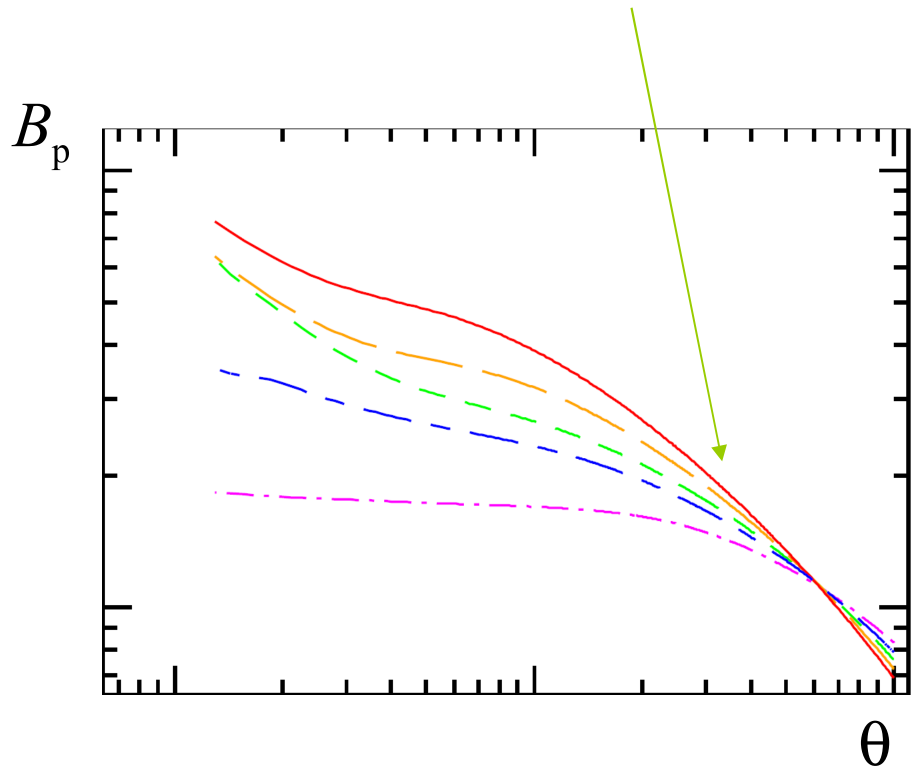


S.Komissarov, M.Barkov, N.Vlahakis, A.Königl. MNRAS, **380**, 51 (2006)

Central core

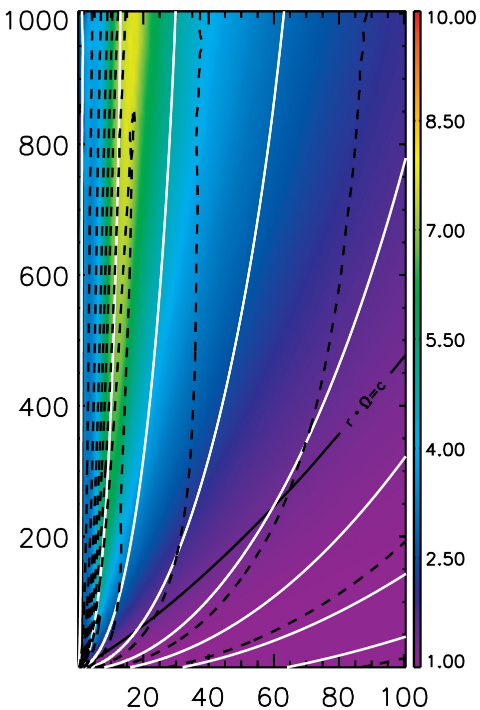
$$B_{\min} = \frac{1}{\sigma_{\mathrm{M}}\gamma_{\mathrm{in}}} B(R_{\mathrm{L}})$$

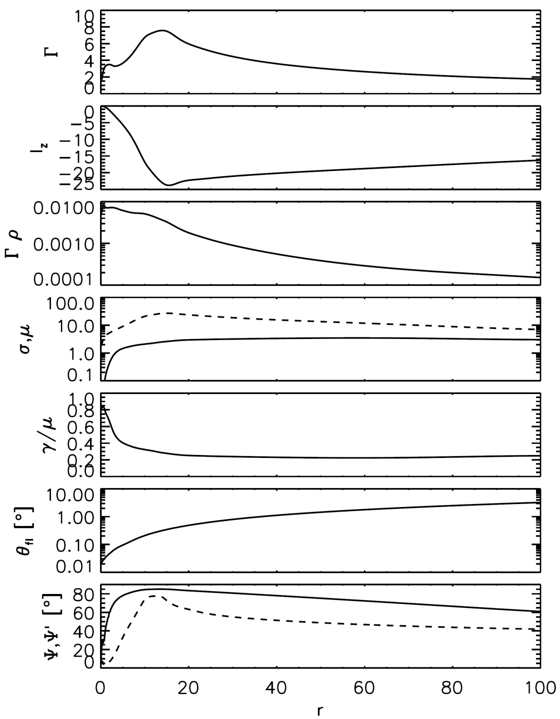


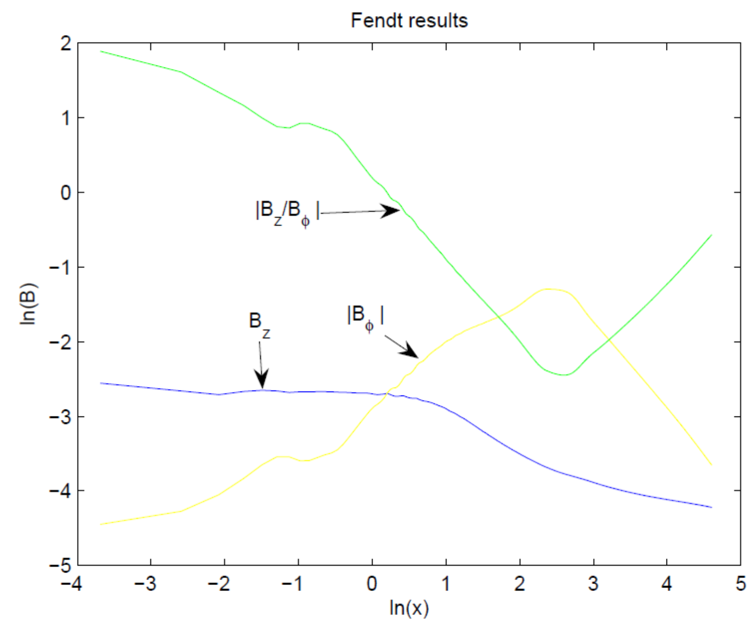


A.Tchekhovskoy, J.McKinney, R.Narayan. ApJ, **699**, 1789 (2009)

Central core







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

Jets – theory

Magnetization – multiplication connection

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

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

MHD ‘central engine’ energy losses

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

After some algebra

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

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

Jets – theory

- Real parameters

$$\begin{cases} \sigma_M \sim \frac{1}{\lambda}\left(\frac{W_{tot}}{W_A}\right)^{1/2} \\ W_A = m_e^2 c^5/e^2 \approx 10^{17}\ \mathrm{erg\ s^{-1}} \end{cases}$$

$$\sigma_M \lambda \sim 10^{14}$$

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

1. Magnetically dominated flow

$$\sigma_M > 10^5 \qquad \Gamma \sim 10^4 - 10^5$$

2. Saturation regime

$$\sigma_M < 10^5 \qquad \Gamma \sim \sigma_M$$

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 $\Gamma m c^2$).

$$\Gamma \sim \sigma_{\rm M}$$

- 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)

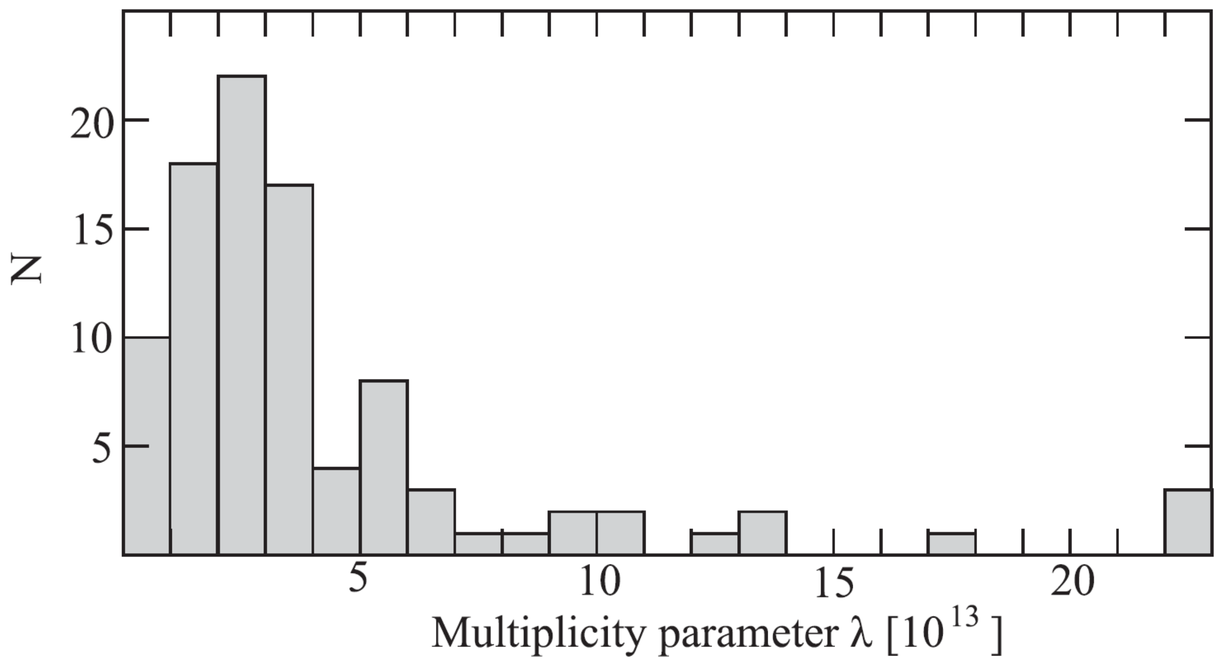


Figure 1. Distributions of the multiplicity parameter λ for the sample of 97 sources. Two objects with $\lambda = 2.8 \times 10^{14}$ and 3.6×10^{14} lie out of the shown range of values.

Core shift and jet parameters

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

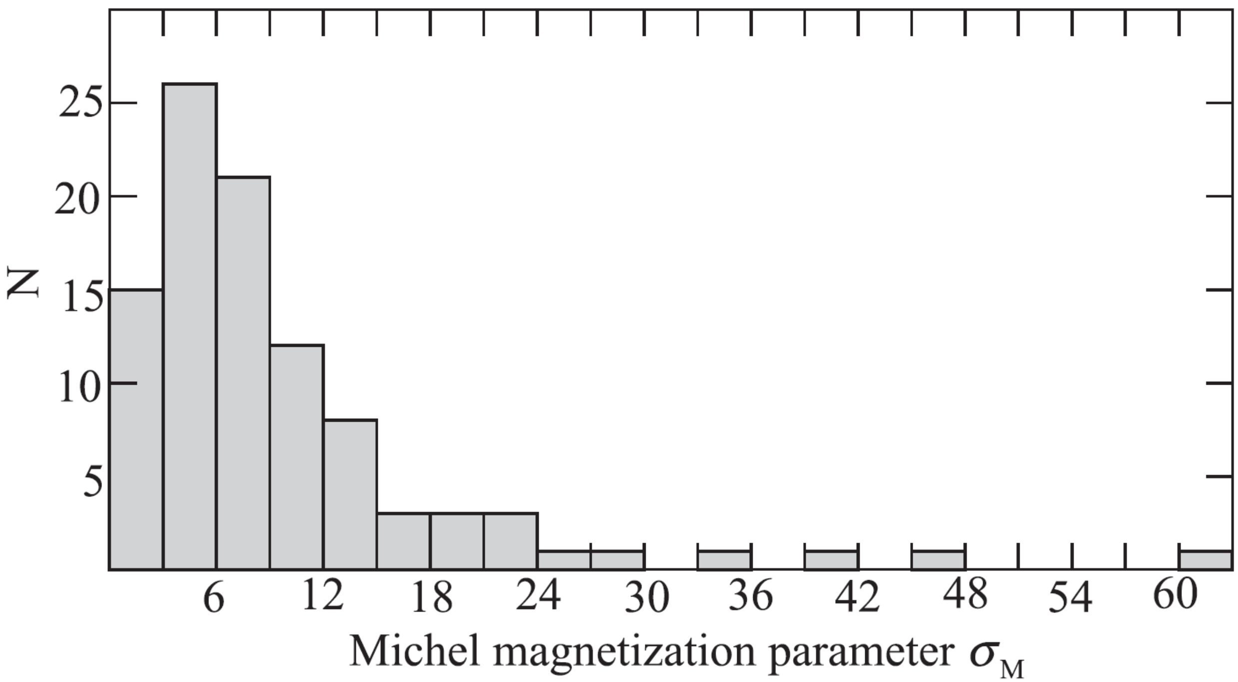


Figure 2. Distributions of the Michel magnetization parameter σ_M for the sample of 97 sources.

Core shift and jet parameters

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

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

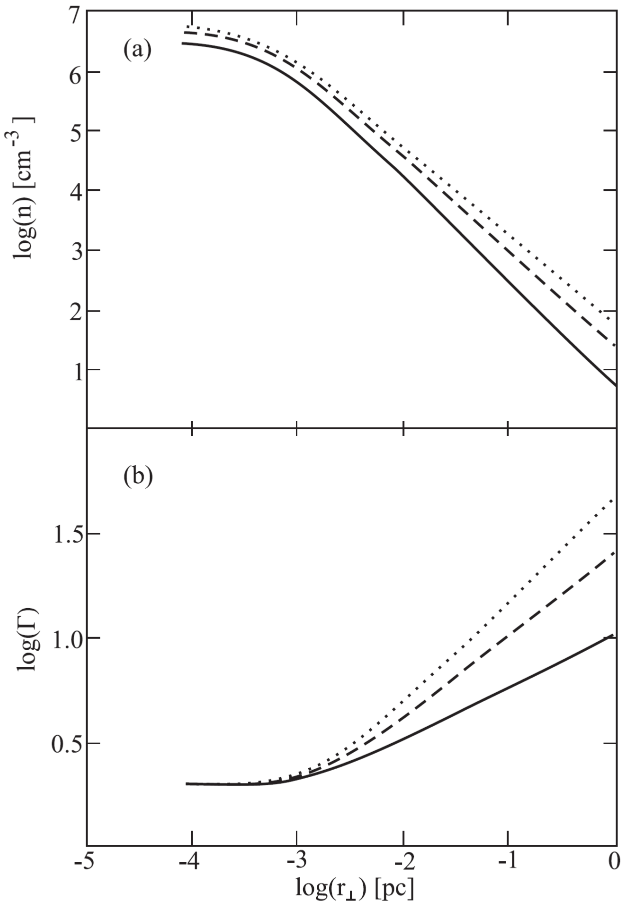


Figure 3. Transversal profile of the number density n_e (a) and Lorentz factor Γ (b) in logarithmical scale for $\lambda = 10^{13}$, jet radius $R_{jet} = 1$ pc and three different values of σ: 5 (solid line), 15 (dashed line) and 30 (dotted line).

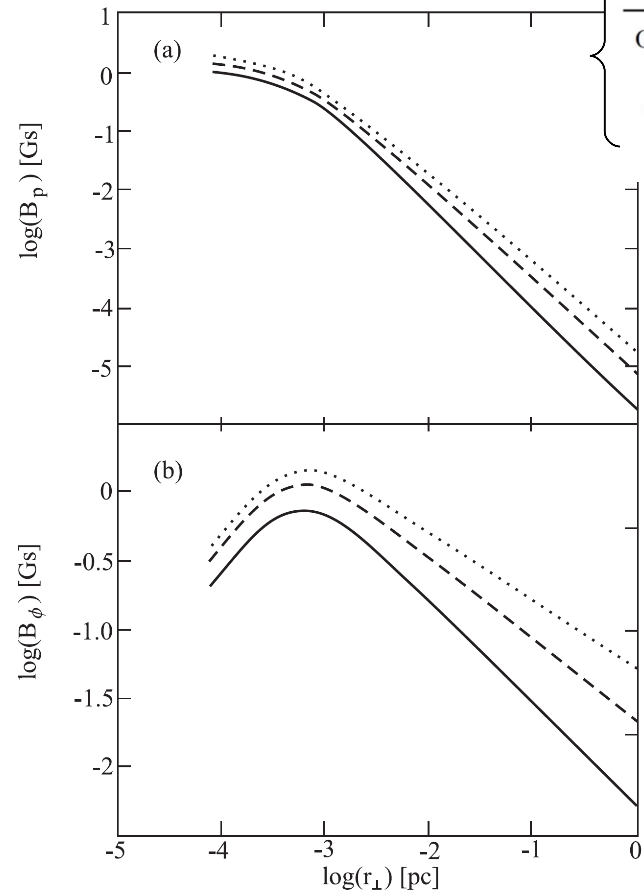


Figure 4. Transversal profile of poloidal (a) and toroidal (b) components of magnetic field in logarithmical scale for the same parameters and line types as in Fig. 3.

Core shift and jet parameters

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

Slow acceleration along the jet

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

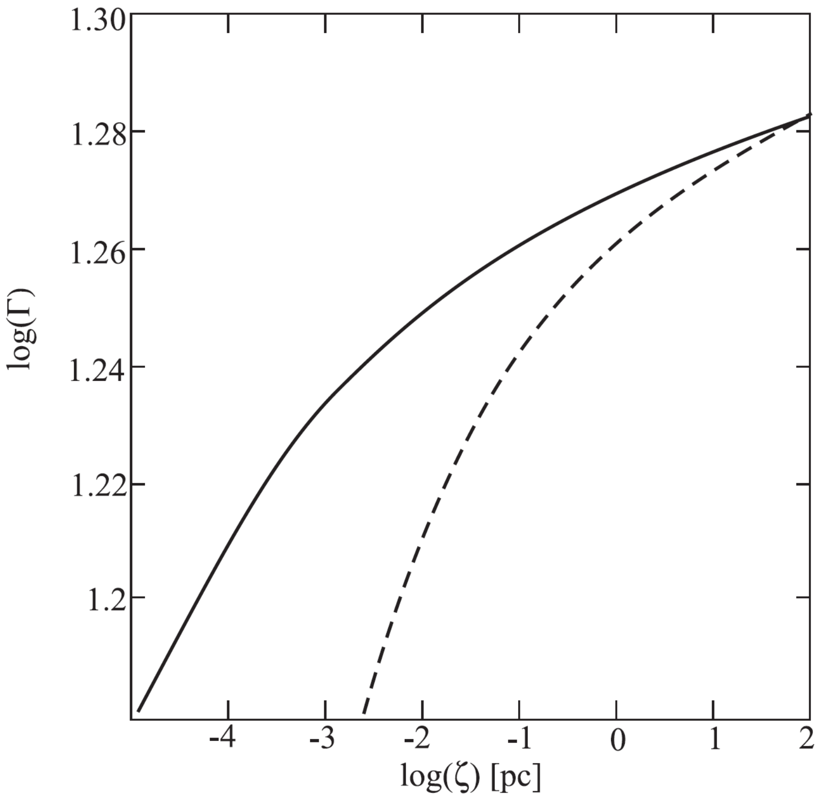


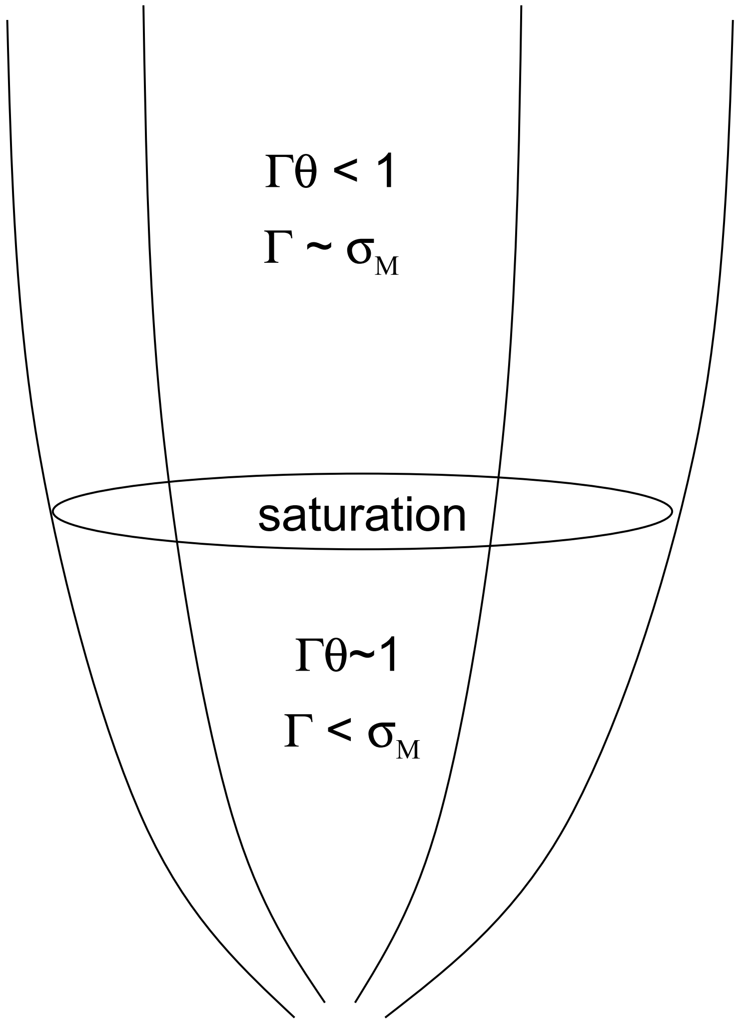
Figure 5. Dependence of Lorentz factor on coordinate along the jet in assumption of $\zeta \propto r_{\perp}^{3}$ (solid line) and $\zeta \propto r_{\perp}^{2}$ (dashed line) form of the jet.

Collimation parameter

For magnetically dominated flow
the theory prediction is

$$\Gamma\theta \sim 1$$

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

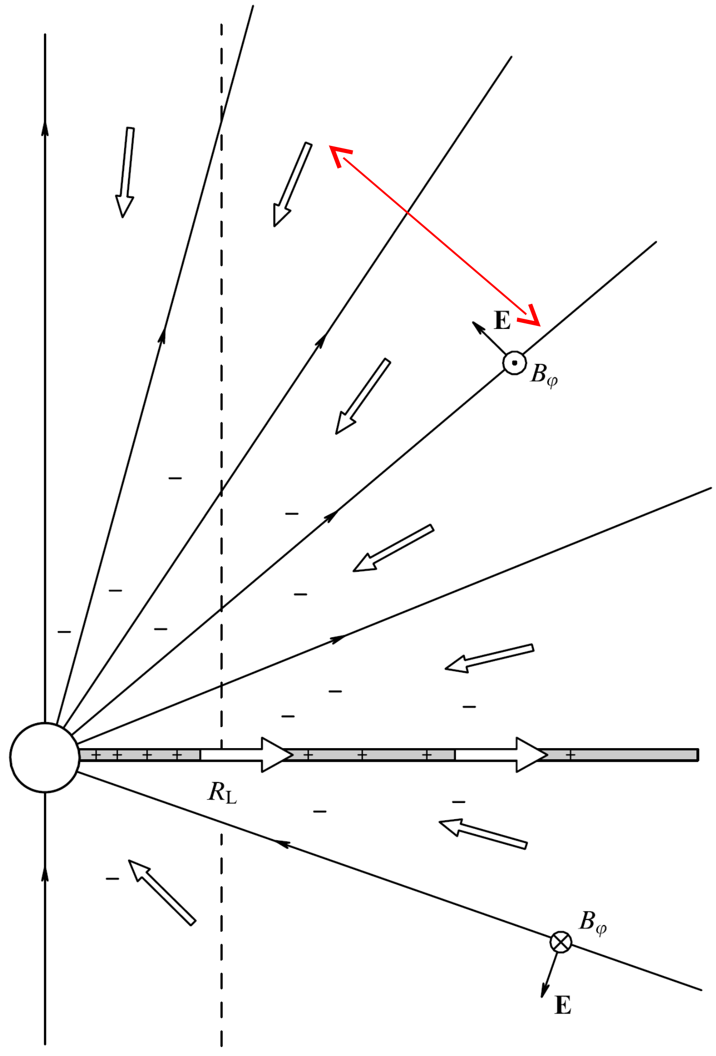


Main conclusions

- Saturation
- Central core

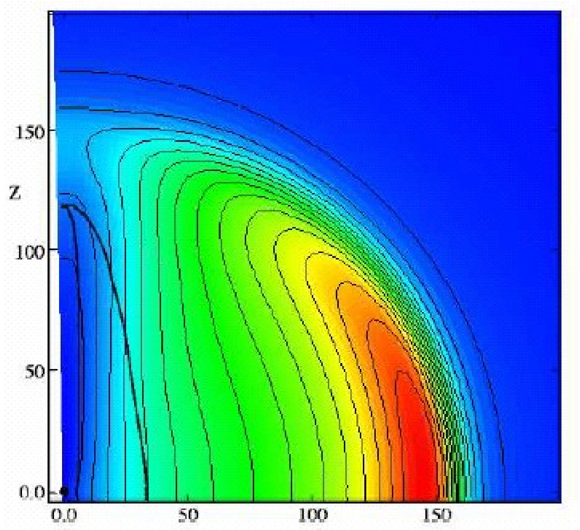
A problem

F.C.Michel (1973)

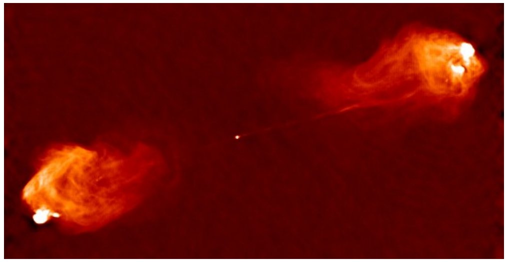


A problem

Switch-on wave, if there is no ambient pressure



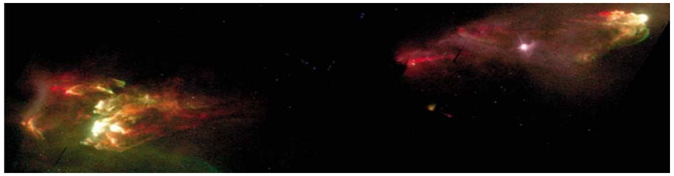
S.Komissarov, MNRAS,**350**, 1431 (2004)



But what to do if we have it?

Lobes in AGN

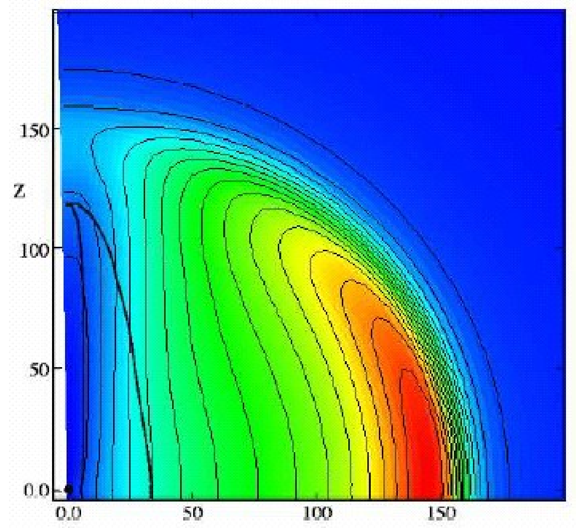
HH objects in YSO



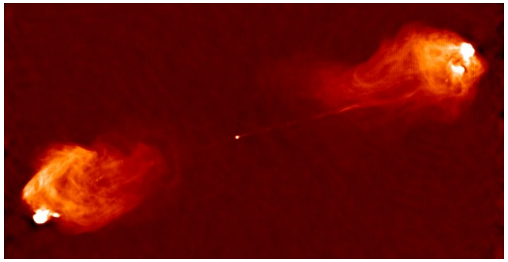
Stellar wind in close binaries

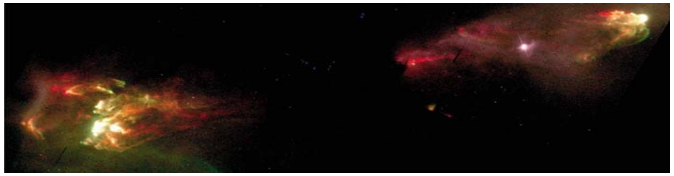
A problem

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?

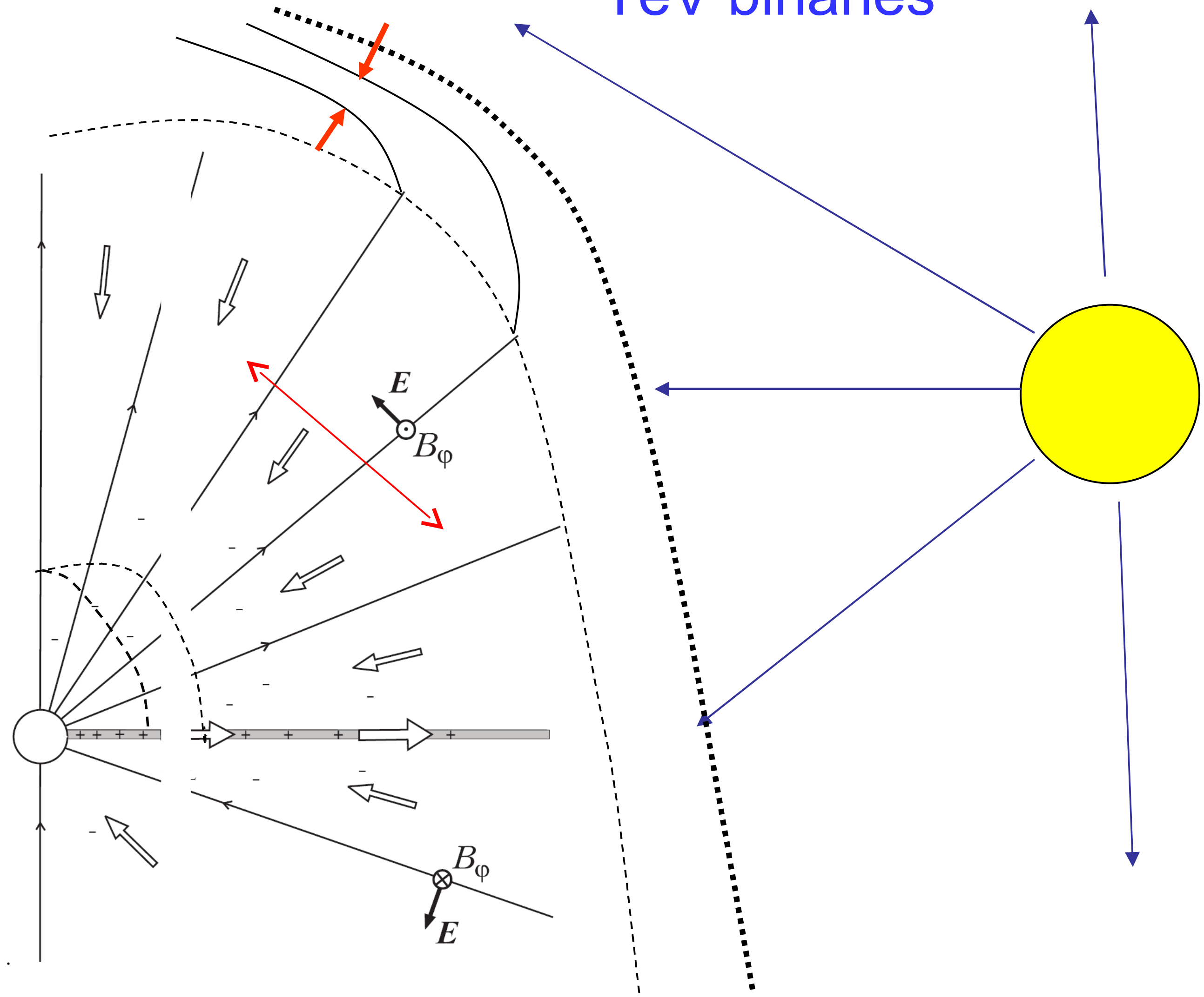
Lobes in AGN

HH objects in YSOs

Stellar wind in binaries

A problem

TeV binaries



A problem

Longitudinal electric field

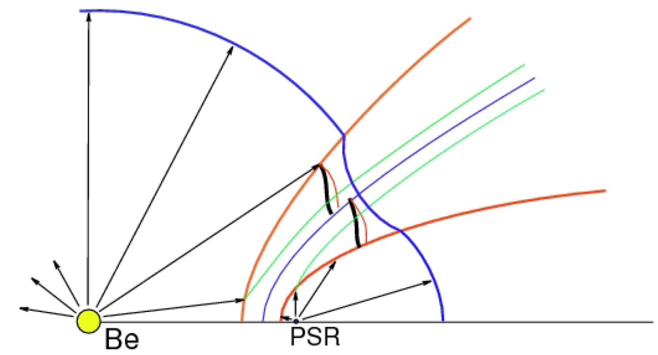
Magnetically dominated wind → Any disturbance → Longitudinal electric field

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

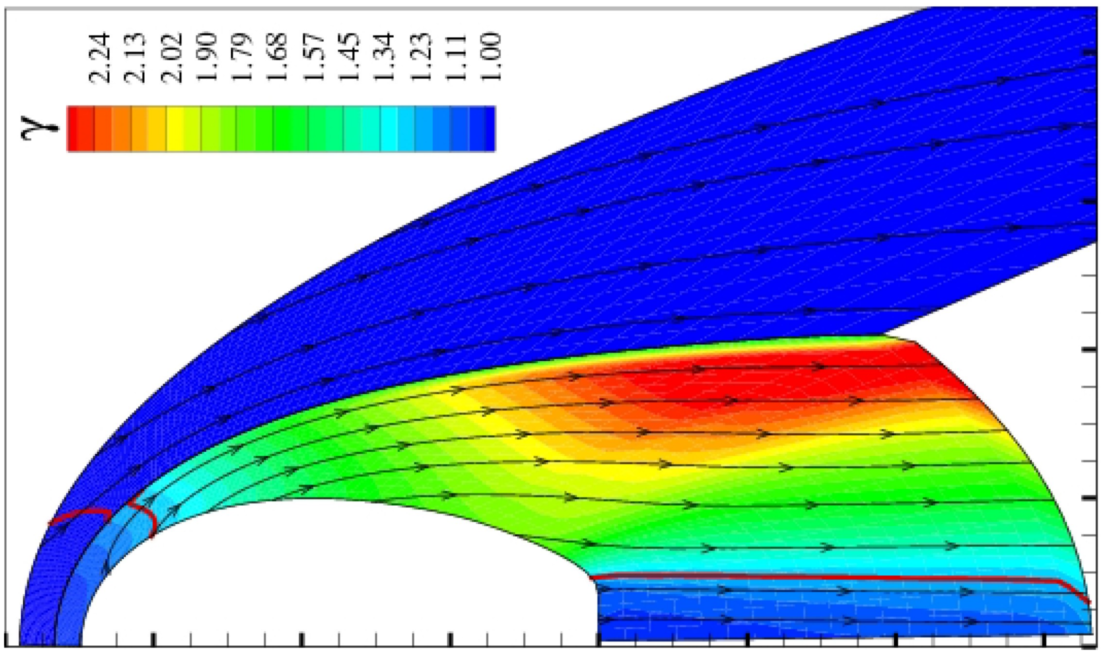
Statement #1

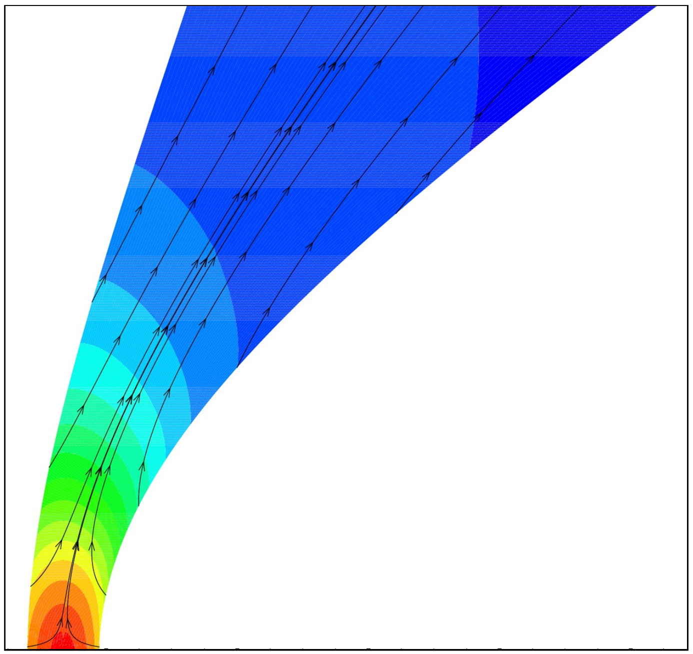
NOONE HAS ANALYZED CARFULLY ENOUGH THE PRESENCE OF THE TRANSVERSE POTENTIAL DROP WHEN THE HIGHLY MAGNETIZED WIND MEETS THE TARGET.

An example



!

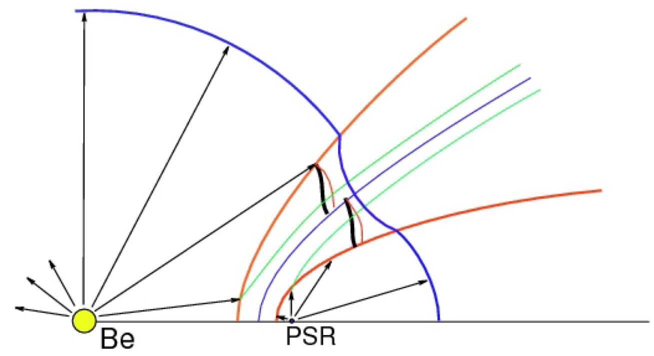


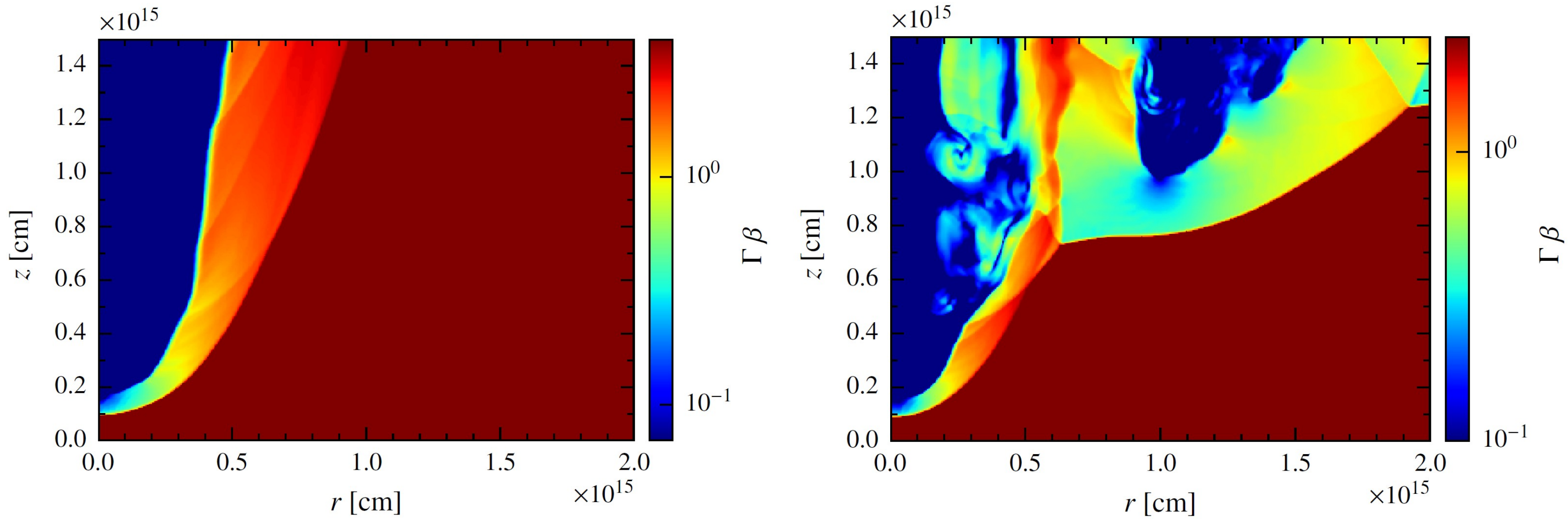


S.V.Bogovalov, D.Khangulyan, A.V.Koldoba, G.V.Ustyugova, F.Aharonian,
MNRAS, **387**, 63 (2008) MNRAS **419**, 3426 (2012)

An example

!

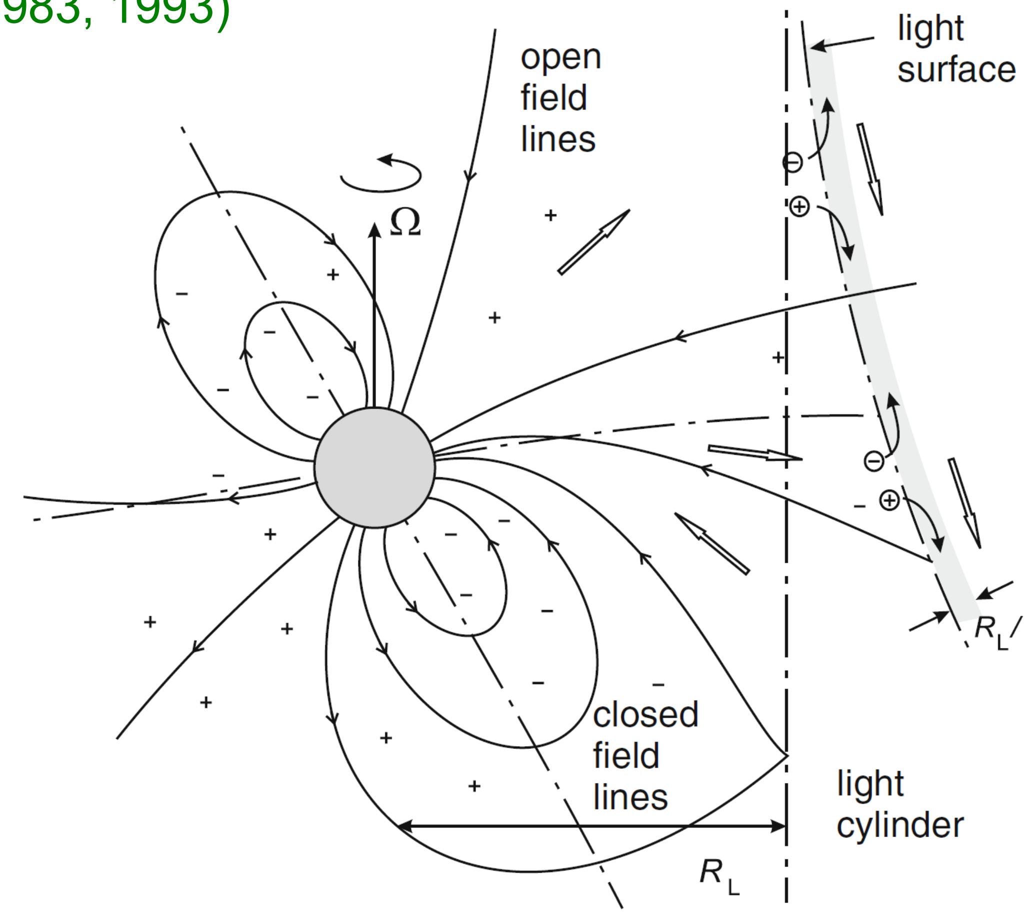




de la Cita et al, (2016) http://arxiv.org/abs/1604.02070

Our predictions

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

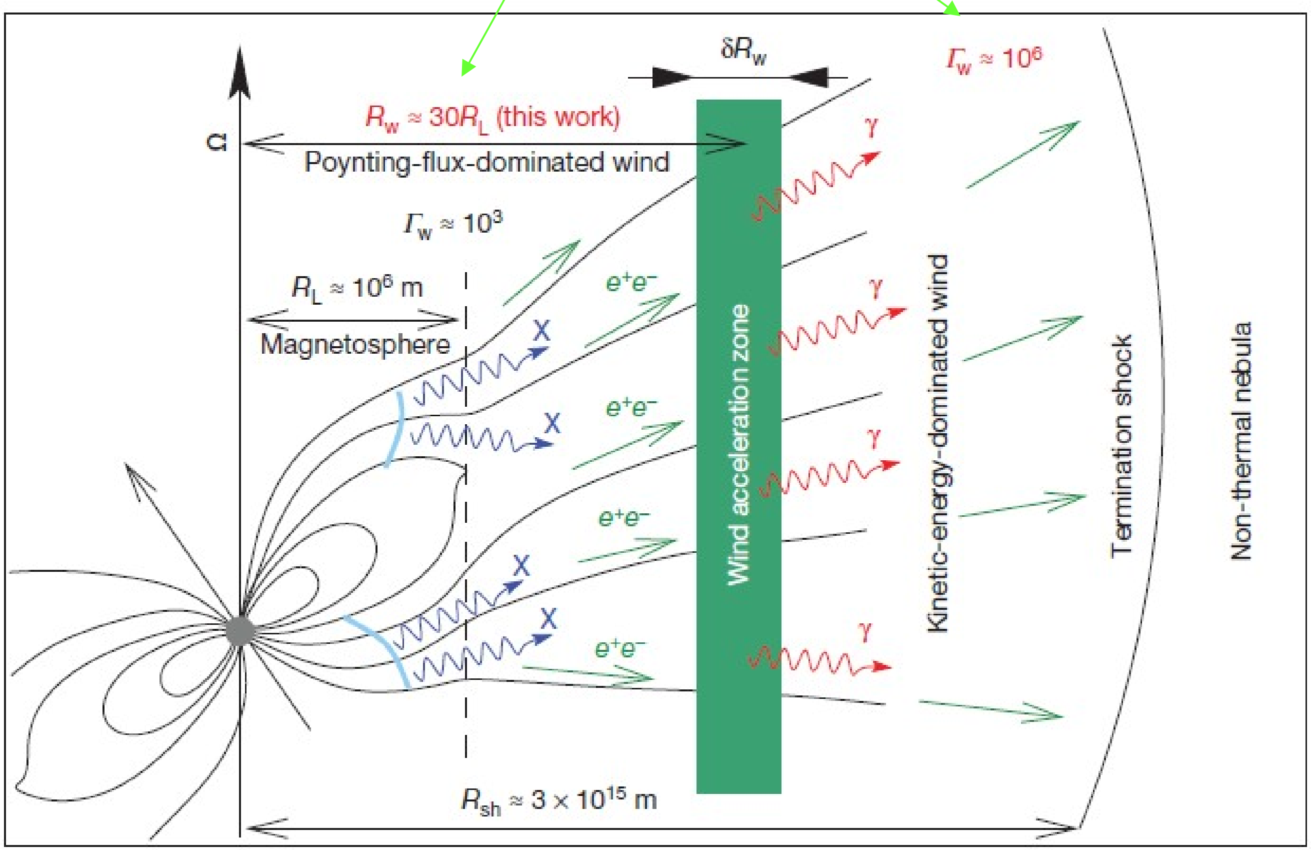


- narrow sheet $\Delta r \sim R_L/\lambda$
- effective particle acceleration up to $\Gamma \sim \sigma_M$ (10^6 for Crab)
- transverse displacement $\Delta r \sim R_L/\lambda$
- Stop point!

doi:10.1038/nature10793

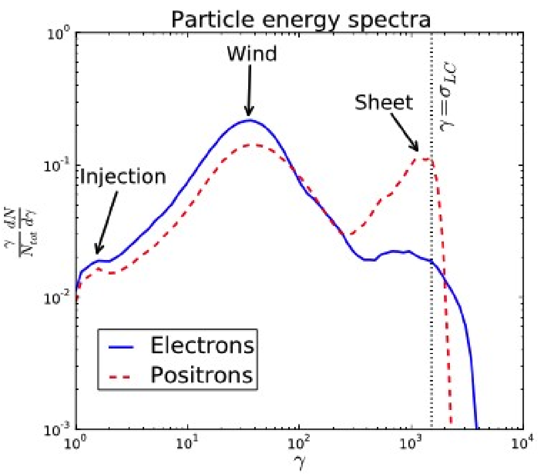
Abrupt acceleration of a 'cold' ultrarelativistic wind from the Crab pulsar

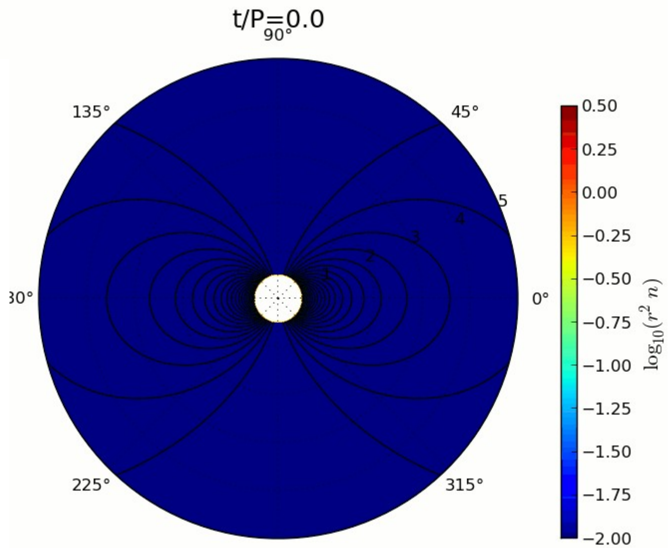
F. A. Aharonian[1,2], S. V. Bogovalov[3] & D. Khangulyan[4]

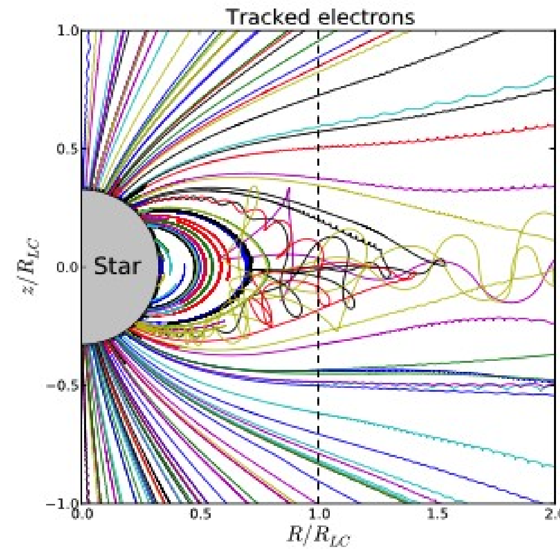


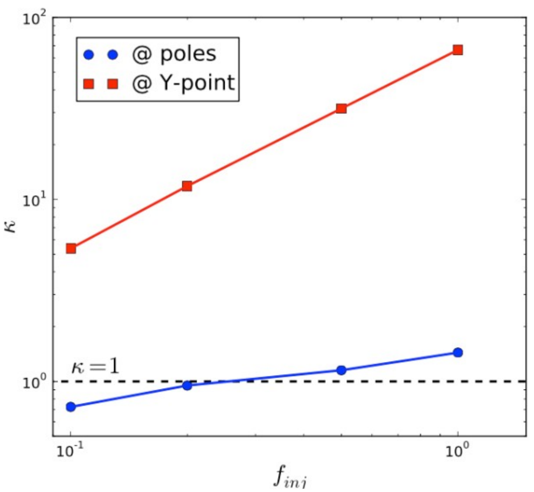
Particle in cell (PIC)

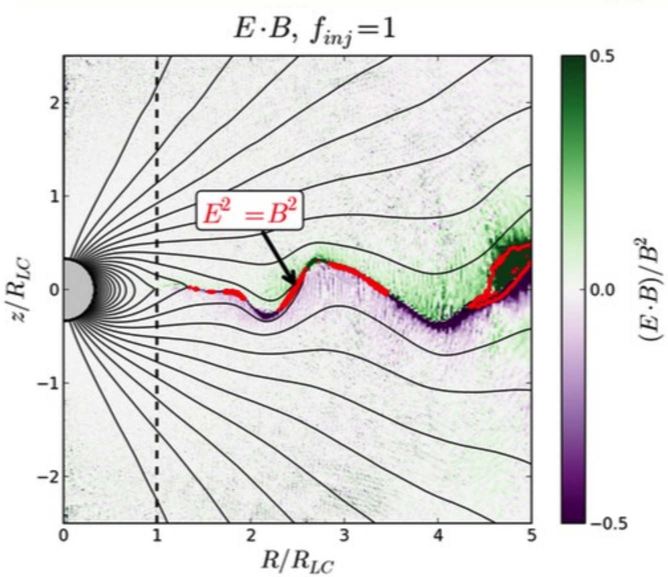
Cerutti B., A.Philippov, Parfrey K., Spitkovsky A.
MNRAS, **448**, 606 (2015)

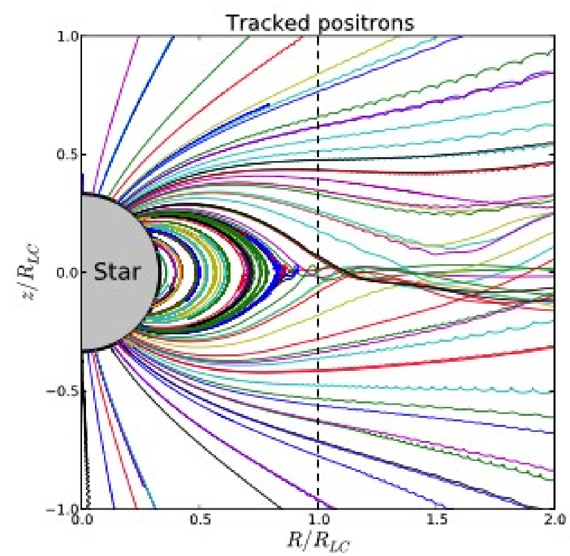












Deceleration

Photon drag

Zhi-Yun Li, M.Begelman, T.Chiueh, ApJ, **384**, 567 (1992)

VB, N.Zakamska, H.Sol, MNRAS, **347**, 587 (2004)

M.Russo, Ch.Thompson, ApJ, **773**, 24 (2013)

Particle loading (poster by VB, E.E.Nokhrina)

R.Svensson, MNRAS, **227**, 403 (1987)

M.Lyutikov, MNRAS, **339**, 632 (2003)

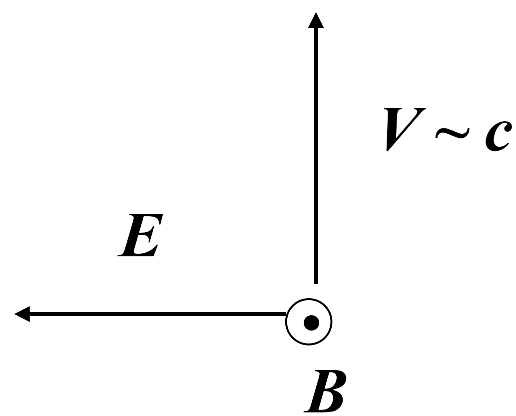
E.V.Derishev, F.Aharonian, V.V.Kocharovsky, Vl.V.Kocharovsky, Phys.Rev.D, **68**, 043003 (2003)

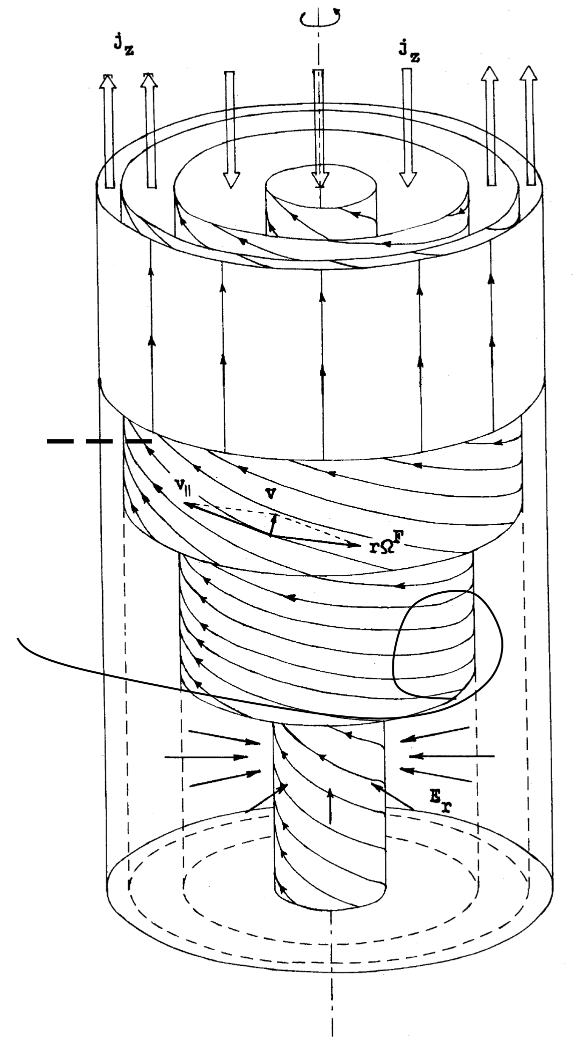
B.Stern, J.Poutanen, MNRAS, 372,1217 (2006)

M.Barkov et al., arXiv:1502.02383

Photon drag

MHD flow + isotropic radiation field

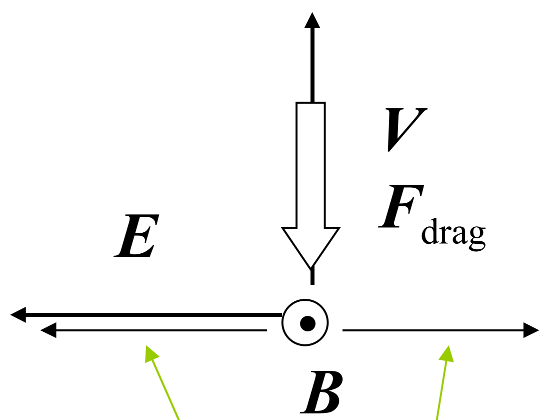


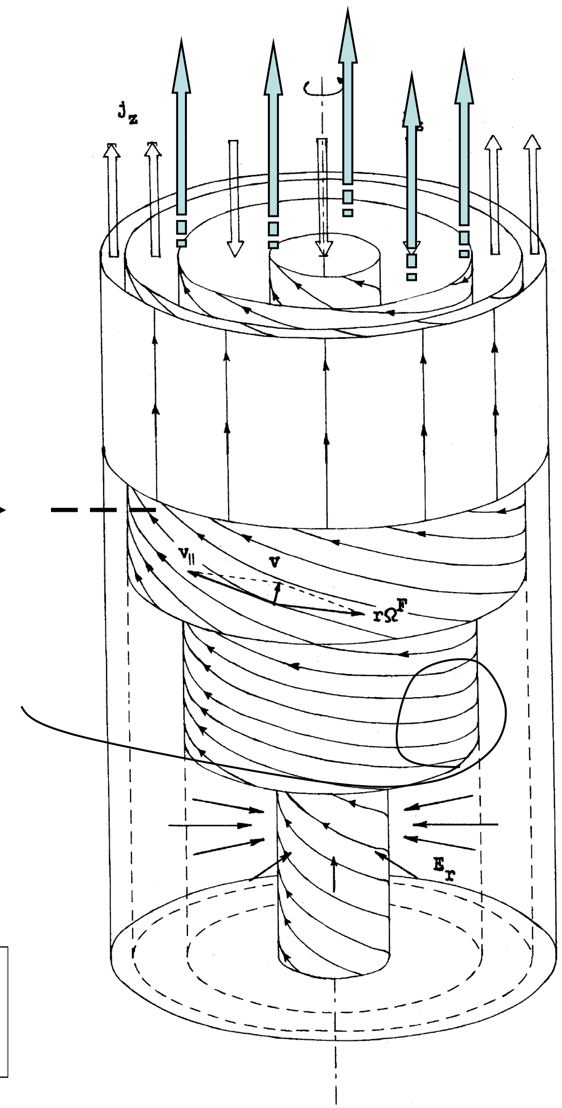


Photon drag

IC

[MHD flow + isotropic radiation field]





No work if the force is orthogonal to magnetic field

But IC photons take the energy away.

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

Photon drag

IC

MHD flow + isotropic radiation field

$$j_r \sim \lambda \rho_{\rm GJ} V_{\rm d}$$

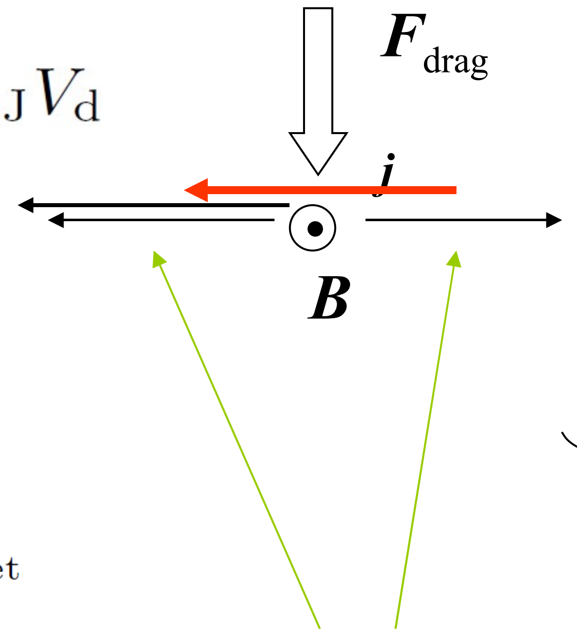
$$\nabla \mathbf{S} = -\mathbf{j}\,\mathbf{E}$$

$$\frac{c}{4\pi}\frac{\mathrm{d}B_\varphi^2}{\mathrm{d}z} \approx j_r B_\varphi$$

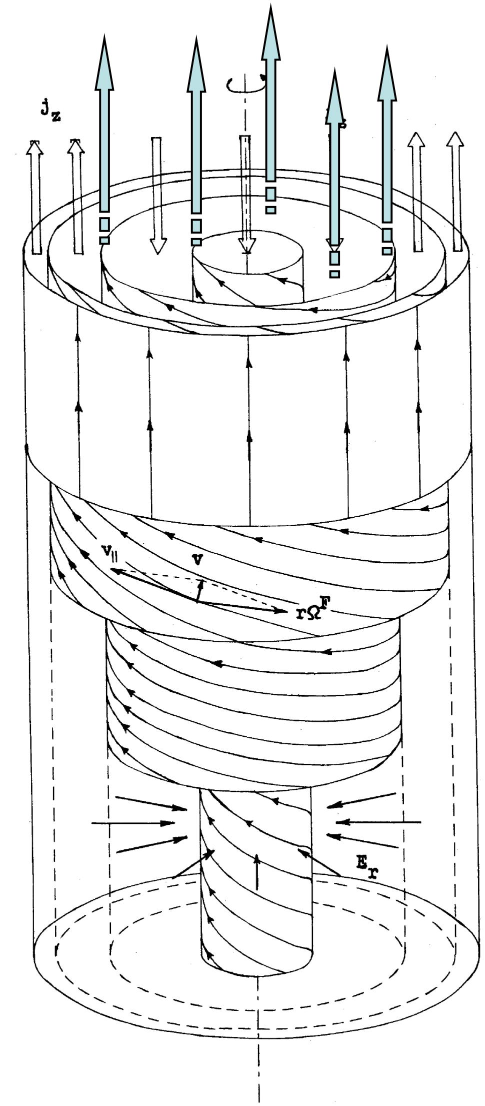
$$B_\varphi / B_z \sim r_{\rm jet}/R_{\rm L}$$

$$W_{\rm tot} \sim (c/4\pi) B_\varphi^2 r_{\rm jet}^2$$

$$L_{\rm dr} \sim \sigma_{\rm M}\frac{m_{\rm e}c^2}{F_{\rm drag}}$$



$$V_{\rm d} \sim c\frac{F_{\rm drag}}{eB_\varphi}$$



Photon drag

IC

MHD flow + isotropic radiation field

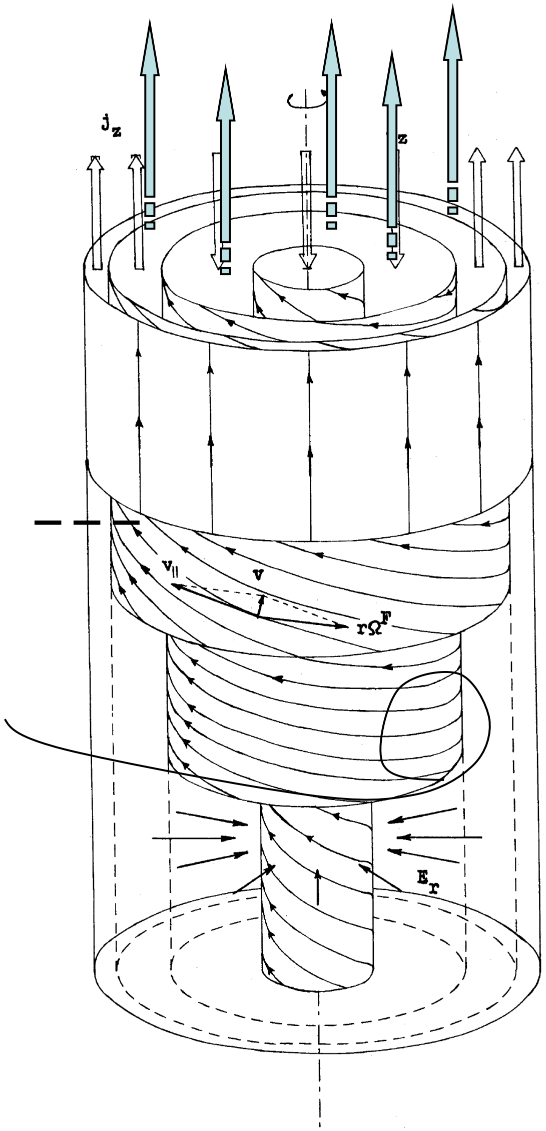
Damping length

$$L_{\mathrm{dr}} \sim \sigma_{\mathrm{M}} \frac{m_{\mathrm{e}}c^2}{F_{\mathrm{drag}}}$$

Appropriate work

$$A_{\mathrm{dr}} \sim \sigma_{\mathrm{M}} m_{\mathrm{e}} c^2$$

And IC photons take the energy away.



Photon drag

MHD flow + isotropic radiation field

Zero force-free approximation

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

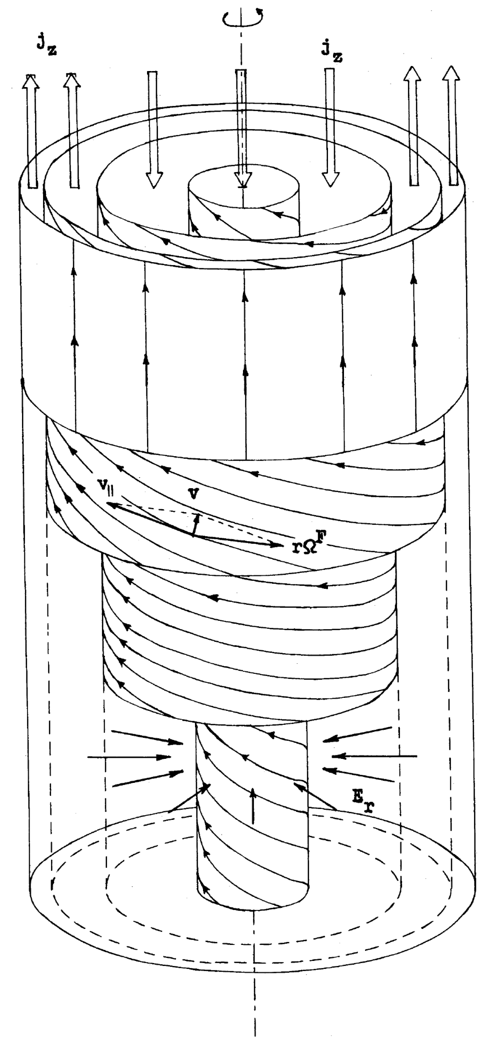
$$\begin{cases} \mathbf{B} = \dfrac{\nabla\Psi \times \mathbf{e}_\varphi}{2\pi r_\perp} - \dfrac{2I}{c r_\perp}\mathbf{e}_\varphi, \\ \mathbf{E} = -\dfrac{\Omega_{\mathrm{F}}(\Psi)}{2\pi c}\nabla\Psi. \end{cases}$$

$$4\pi I(\Psi) = 2\Omega_F(\Psi)\Psi$$

$$B_z^0 = B_0$$

$$B_\varphi^{(0)} = -\frac{2I}{c r_\perp},$$

$$E_r^{(0)} = B_\varphi^0,$$



Photon drag

MHD flow + isotropic radiation field

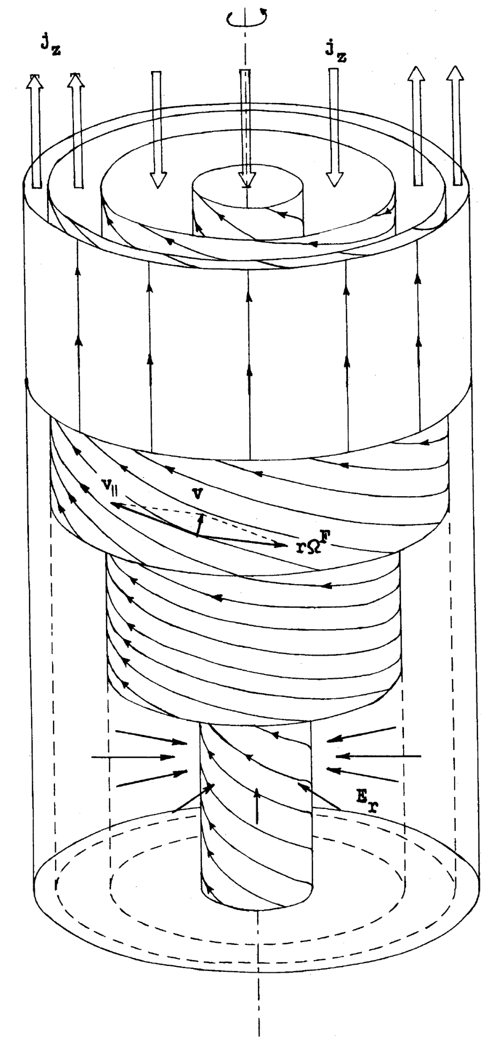
MHD disturbances

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

$$
\begin{aligned}
\Phi(r_\perp, z) &= \frac{B_0}{c}\left[\int_0^{r_\perp}\Omega_\mathrm{F}(r')r'\mathrm{d}r' + \Omega_0 r_\perp^2\delta(r_\perp, z)\right], \\
\Psi(r_\perp, z) &= \pi B_0 r_\perp^2\left[1 + \varepsilon f(r_\perp, z)\right].
\end{aligned}
$$

$\delta \sim 1$

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

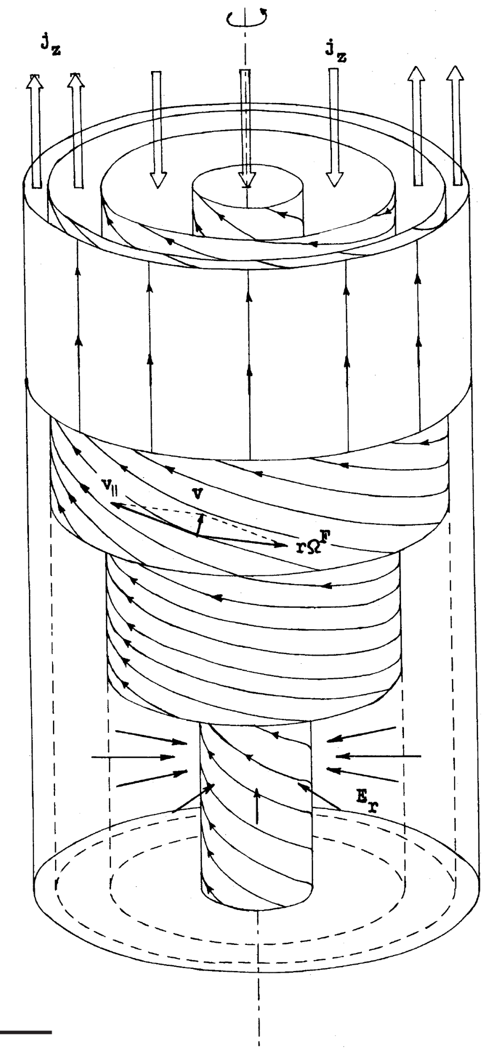


Photon drag – the task

MHD flow + radiation field

How the photon drag affects the MHD flow

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



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

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

$$U = U_{\rm iso} = \eta\frac{L_{\rm tot}}{4\pi r^2_{\rm cloud}c}$$

Photon drag

MHD flow + isotropic radiation field

MHD disturbances + drag

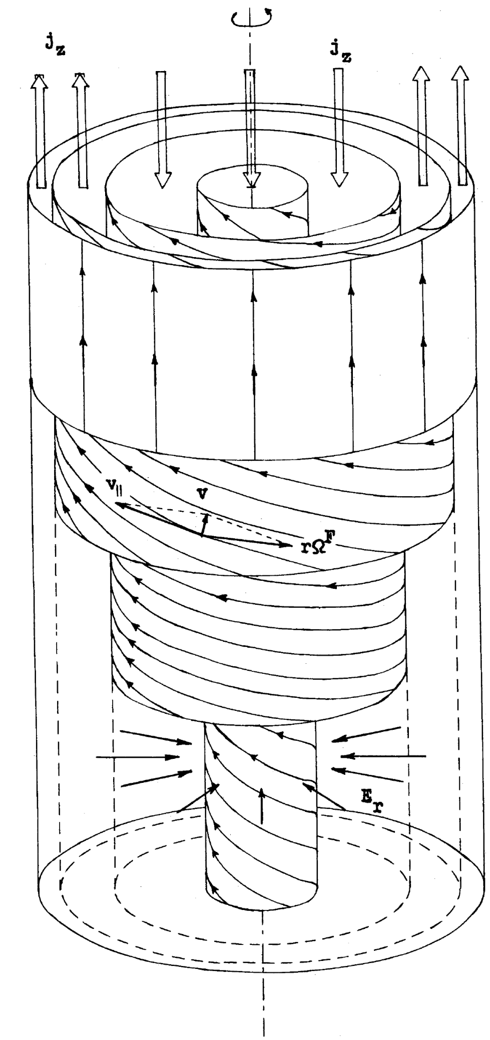
$$
\left\{
\begin{aligned}
&-\frac{1}{r_\perp}\frac{\partial}{\partial r_\perp}(r_\perp^2\zeta) = \\
&2(\eta^+ - \eta^-) - 2\left[(\lambda - K)\,\xi_z^+ - (\lambda + K)\,\xi_z^-\right], \\
&2(\eta^+ - \eta^-) + \frac{1}{r_\perp}\frac{\partial}{\partial r_\perp}\left[r_\perp\frac{\partial}{\partial r_\perp}\left(r_\perp^2\delta\right)\right]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

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

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

$$F_{\mathrm{d}} = \frac{4}{3}\,\frac{\sigma_{\mathrm{T}} U_{\mathrm{iso}}}{m_{\mathrm{e}} c^2}$$

with N.Zakamska



Photon drag

MHD flow + isotropic radiation field

Step I: MHD disturbances *without* drag

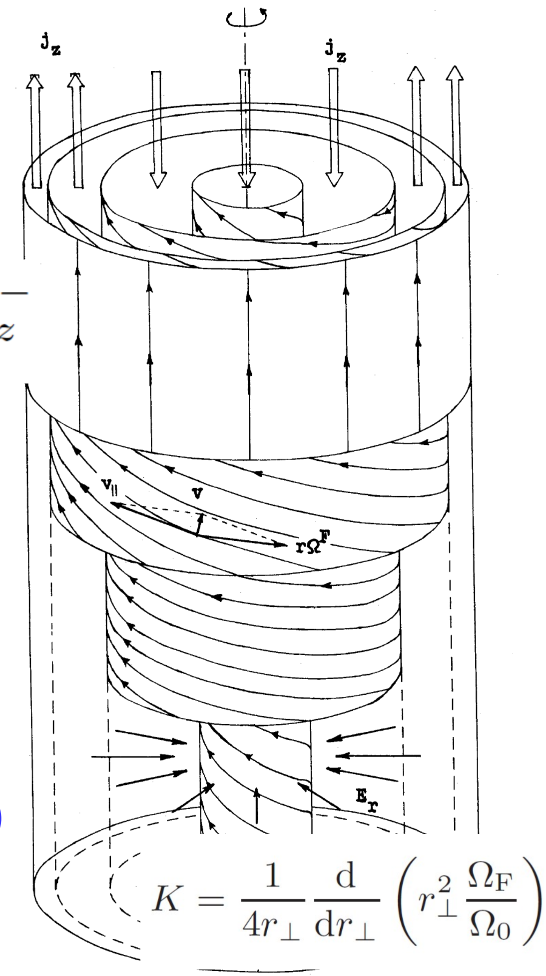
$$
\left\{
\begin{aligned}
& -\frac{1}{r_\perp}\frac{\partial}{\partial r_\perp}(r_\perp^2\zeta) = \\
& 2(\eta^+ - \eta^-) - 2\left[(\lambda - K)\,\xi_z^+ - (\lambda + K)\,\xi_z^-\right], \\
& 2(\eta^+ - \eta^-) + \frac{1}{r_\perp}\frac{\partial}{\partial r_\perp}\left[r_\perp\frac{\partial}{\partial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

$$(\lambda - K)\,\xi_z^+ = (\lambda + K)\,\xi_z^-$$

$$\xi_\varphi^\pm = x\xi_z^\pm$$

$$\xi_r^\pm = 0$$

- Force-free structure remains the exact MHD solution (i.e. finite particle energy)



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

$$x = \Omega_{\mathrm{F}}(r_\perp)r_\perp/c$$

Photon drag

MHD flow + isotropic radiation field

Step I: MHD disturbances *without* drag

$$
\left\{
\begin{aligned}
&-\frac{1}{r_\perp}\frac{\partial}{\partial r_\perp}(r_\perp^2\zeta) = \\
&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}(r_\perp^2\delta)\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}(r_\perp^2 f) = \\
&4\,\frac{\Omega_0 r_\perp}{c}\left[(\lambda - K)\,\xi_\varphi^+ - (\lambda + K)\,\xi_\varphi^-\right], \\
&\frac{\partial}{\partial z}(\xi_r^+\gamma^+) = -\xi_r^+ F_{\rm d}(\gamma^+)^2 \\
&+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}(\xi_r^-\gamma^-) = -\xi_r^- F_{\rm d}(\gamma^-)^2 \\
&-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}(\gamma^+) = -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}(\gamma^-) = -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}(\xi_\varphi^+\gamma^+) = -\xi_\varphi^+ F_{\rm d}(\gamma^+)^2 \\
&+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}(\xi_\varphi^-\gamma^-) = -\xi_\varphi^- F_{\rm d}(\gamma^-)^2 \\
&-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.
$$

$$(\lambda - K)\,\xi_z^+ = (\lambda + K)\,\xi_z^-$$

$$\xi_\varphi^\pm = x\xi_z^\pm$$

$$\xi_r^\pm = 0$$

- Only one free function

$$\boxed{\Gamma^2 = \Gamma_0^2 + x^2}$$

$$P_+ = \frac{\xi_z^+ + \xi_z^-}{2}$$

$$Q_+ = \frac{\xi_\varphi^+ + \xi_\varphi^-}{2}$$

$$P_- = \xi_z^+ - \xi_z^-$$

$$Q_- = \xi_\varphi^+ - \xi_\varphi^-$$

$$
\begin{aligned}
Q_\pm &= xP_\pm, \\
P_- &= 2\frac{K}{\lambda}P_+, \\
Q_- &= 2\frac{K}{\lambda}Q_+, \\
G &= -\Gamma^3(1 - x^2P_+)P_-
\end{aligned}
$$

$$P_+ = \frac{1}{\Gamma(\Gamma + \sqrt{\Gamma^2 - x^2})}$$

Photon drag

MHD flow + isotropic radiation field

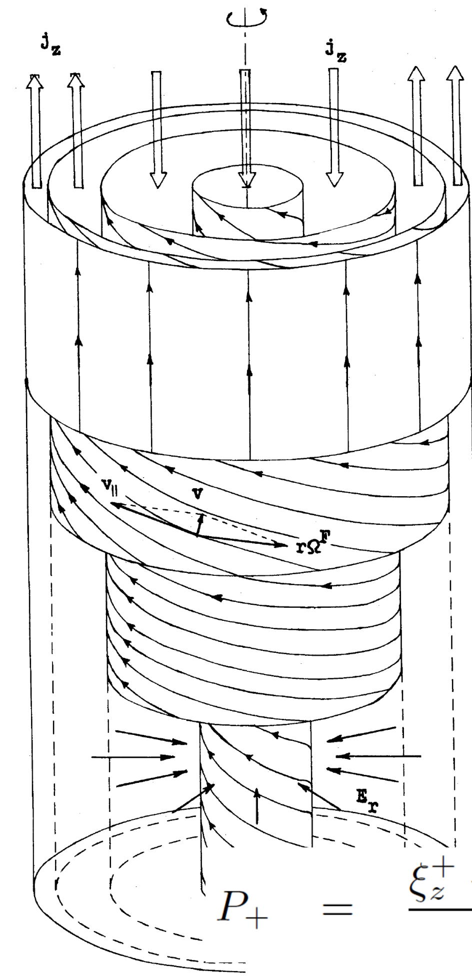
Step II: MHD disturbances *with* drag –
drift approximation

$$\mathbf{V}_{\rm dr} = c\frac{(e\mathbf{E} + \mathbf{F}_{\rm drag}) \times \mathbf{B}}{eB^2}$$

$$\frac{{\rm d}\mathcal{E}}{{\rm d}t} = (\mathbf{F}_{\rm drag} + e\mathbf{E})\mathbf{v}$$

$$\frac{{\rm d}\mathcal{E}}{{\rm d}t} = (F_{\parallel} + eE_{\parallel})v_{\parallel}$$

$$\frac{\partial\gamma^{\pm}}{\partial z} = -\frac{(1-x^2P_+)^2}{(1+x^2)}F_{\rm d}(\gamma^{\pm})^2$$
$$\mp\frac{4\lambda\sigma_{\rm M}}{r_{\rm jet}^2}\frac{(1-x^2P_+)}{(1+x^2)}\left(-r_{\perp}^2\frac{\partial\delta}{\partial z} + r_{\perp}^2\frac{\Omega_{\rm F}}{\Omega_0}\frac{\varepsilon}{2}\frac{\partial f}{\partial z}\right).$$



$$P_+ = \frac{\xi_z^+ + \xi_z^-}{2}$$

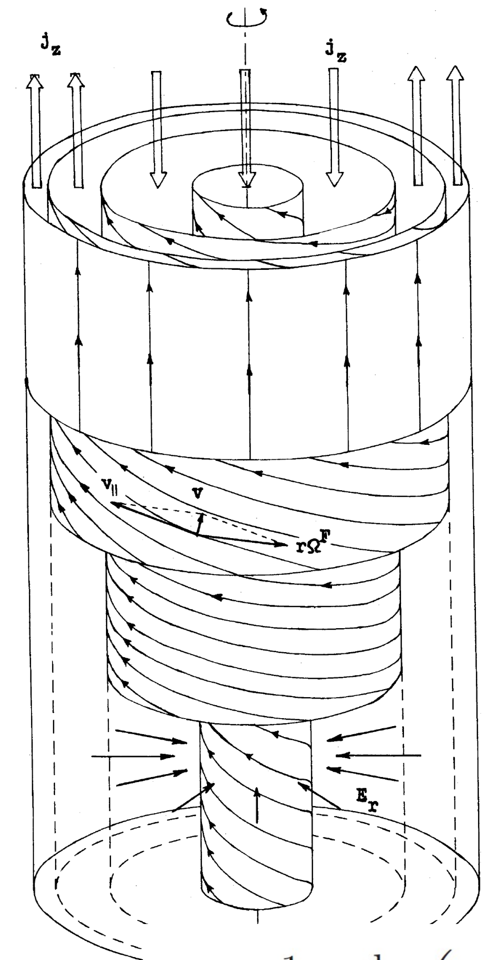
$$F_{\rm d} = \frac{4}{3}\frac{\sigma_{\rm T}U_{\rm iso}}{m_{\rm e}c^2}$$

Photon drag

MHD flow + isotropic radiation field

Step III: Disturbances of electric field and magnetic surfaces (MHD approximation)

$$\delta = \frac{\varepsilon}{2}\frac{\Omega_{\rm F}}{\Omega_0} f$$



$$
\begin{aligned}
&2x\frac{\mathrm{d}}{\mathrm{d}x_0}\left[x_0\frac{\mathrm{d}}{\mathrm{d}x_0}D\right] - 2x_0\frac{\mathrm{d}}{\mathrm{d}x_0}\left[\frac{1}{x_0}\frac{\mathrm{d}}{\mathrm{d}x_0}\left(\frac{\Omega_0}{\Omega_{\rm F}}D\right)\right] + \\
&-8x\frac{\mathrm{d}}{\mathrm{d}x_0}\left[K\frac{(x_0x+\Omega_0/\Omega_{\rm F}-x^2P_+\Omega_0/\Omega_{\rm F})}{(1+x^2)}D\right] + \\
&8Kx_0\frac{\mathrm{d}}{\mathrm{d}x_0}D - \frac{32K^2x_0(x^2+1-x^2P_+)}{x(1+x^2)}D \\
&= -2x\frac{\mathrm{d}}{\mathrm{d}x_0}\left[x_0^2\mathcal{G}\right] - 8Kx_0^2\mathcal{G},
\end{aligned}
$$

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

$$D = x_0^2\delta$$

$$x_0 = \Omega_0 r_\perp/c$$

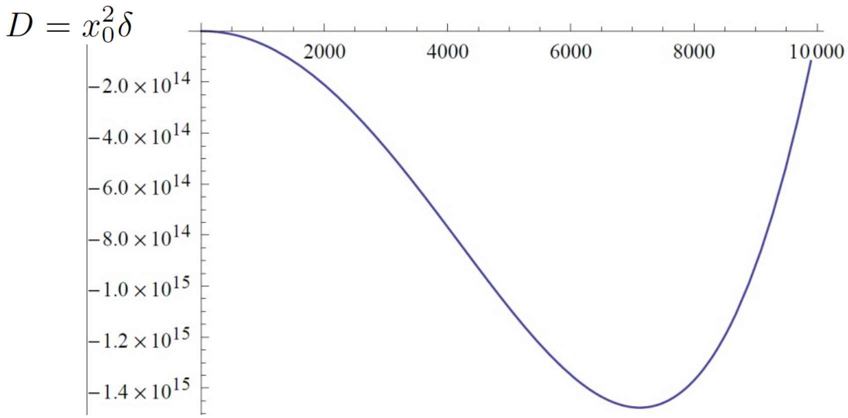
$$\mathcal{G} = A\Gamma^2(F_{\rm d}z)/\sigma_{\rm M}$$

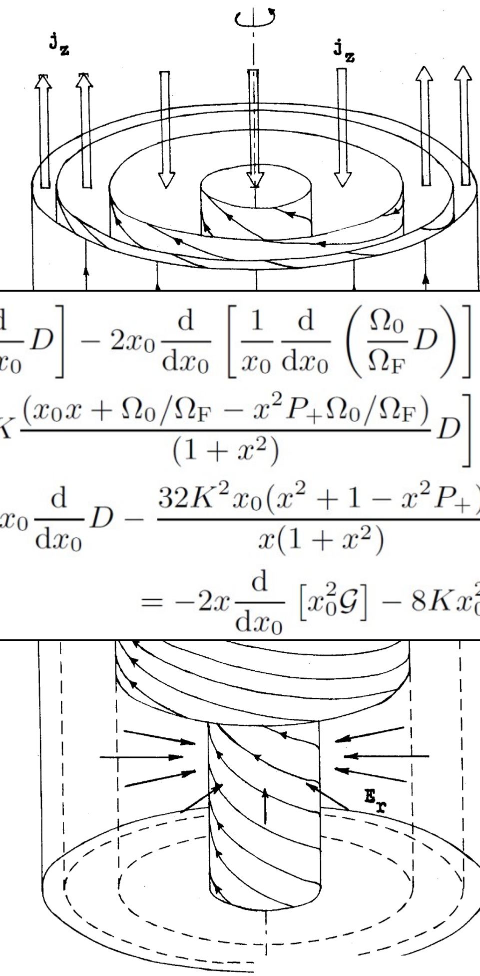
$$x = \Omega(r_\perp)r_\perp/c$$

Photon drag

MHD flow + isotropic radiation field

Step III: Disturbances of electric field and magnetic surfaces (MHD approximation)





$$
\begin{aligned}
&2x\frac{\mathrm{d}}{\mathrm{d}x_0}\left[x_0\frac{\mathrm{d}}{\mathrm{d}x_0}D\right] - 2x_0\frac{\mathrm{d}}{\mathrm{d}x_0}\left[\frac{1}{x_0}\frac{\mathrm{d}}{\mathrm{d}x_0}\left(\frac{\Omega_0}{\Omega_\mathrm{F}}D\right)\right] + \\
&-8x\frac{\mathrm{d}}{\mathrm{d}x_0}\left[K\frac{(x_0x + \Omega_0/\Omega_\mathrm{F} - x^2P_+\Omega_0/\Omega_\mathrm{F})}{(1+x^2)}D\right] + \\
&8Kx_0\frac{\mathrm{d}}{\mathrm{d}x_0}D - \frac{32K^2x_0(x^2+1-x^2P_+)}{x(1+x^2)}D \\
&= -2x\frac{\mathrm{d}}{\mathrm{d}x_0}\left[x_0^2\mathcal{G}\right] - 8Kx_0^2\mathcal{G},
\end{aligned}
$$

$$\delta \sim \frac{A}{\sigma_\mathrm{M}}\Gamma^2(F_\mathrm{d}z) \qquad L_\mathrm{dr} \sim \frac{\sigma_\mathrm{M}}{\Gamma^2F_\mathrm{d}}$$

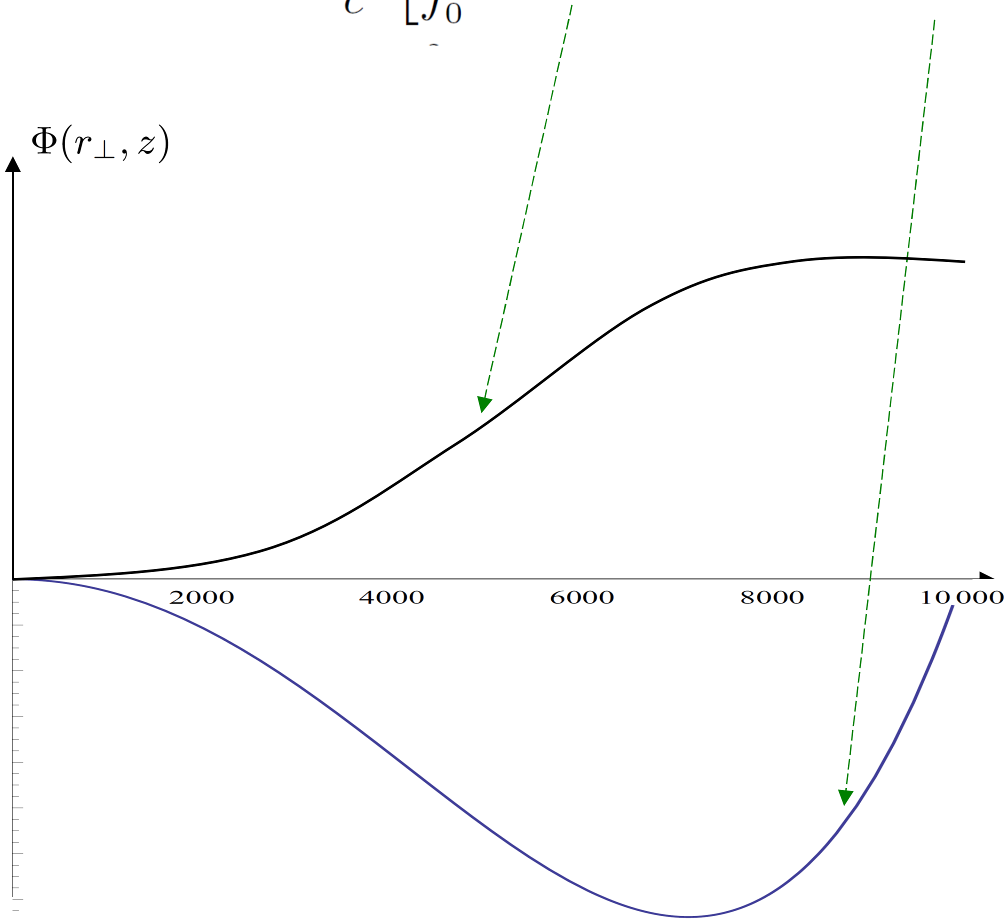
$$L_\mathrm{dr} \sim 300\left(\frac{\sigma_\mathrm{M}}{10}\right)\left(\frac{\Gamma}{10}\right)^{-2}\left(\frac{U_\mathrm{iso}}{10^{-4}\,\mathrm{erg/cm^3}}\right)^{-1}\mathrm{pc}$$

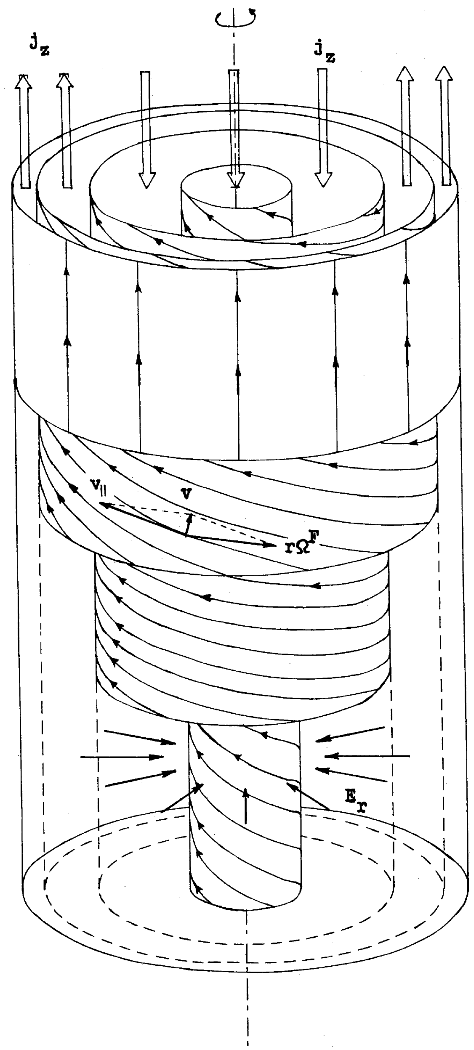
$$F_\mathrm{d} = \frac{4}{3}\frac{\sigma_\mathrm{T}U_\mathrm{iso}}{m_\mathrm{e}c^2}$$

Photon drag

MHD flow + isotropic radiation field

$$\Phi(r_\perp, z) \quad = \quad \frac{B_0}{c}\left[\int_0^{r_\perp} \Omega_\mathrm{F}(r')r'\mathrm{d}r' + \Omega_0 r_\perp^2 \delta(r_\perp, z)\right]$$





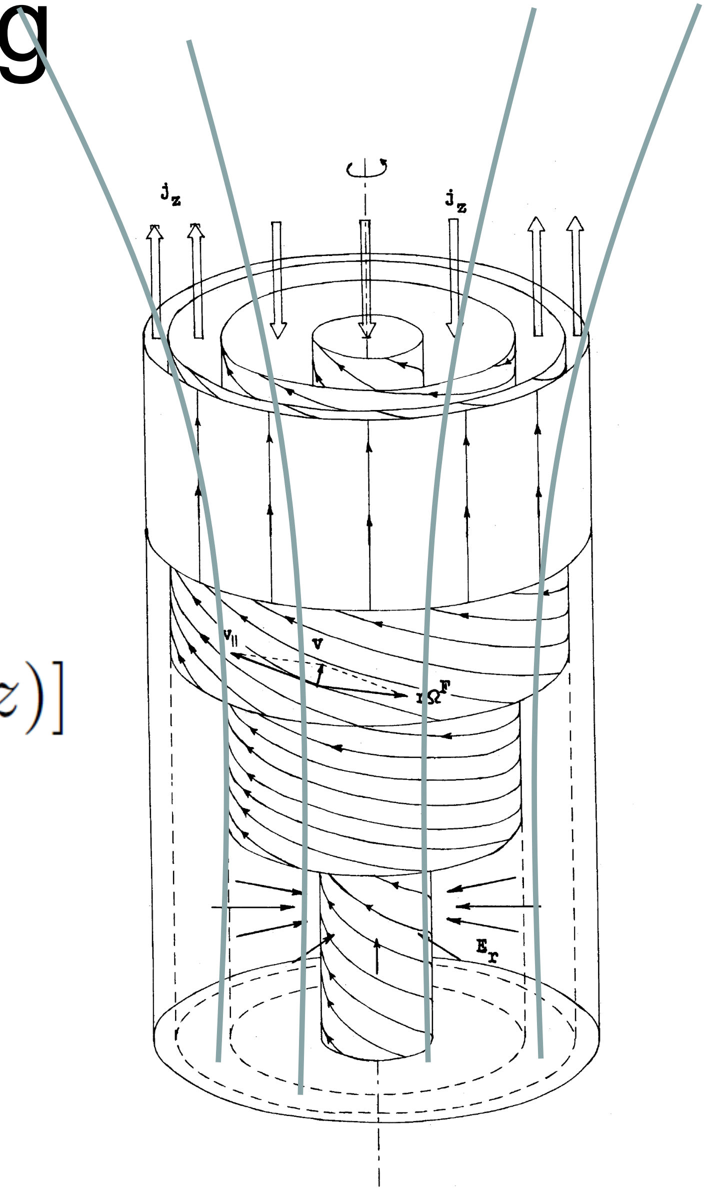
Photon drag

MHD flow + isotropic radiation field

Decolimation

$$\delta = \frac{\varepsilon}{2}\frac{\Omega_{\rm F}}{\Omega_0} f$$

$$\Psi(r_\perp, z) \quad = \quad \pi B_0 r_\perp^2 \left[1 + \varepsilon f(r_\perp, z)\right]$$



Photon drag

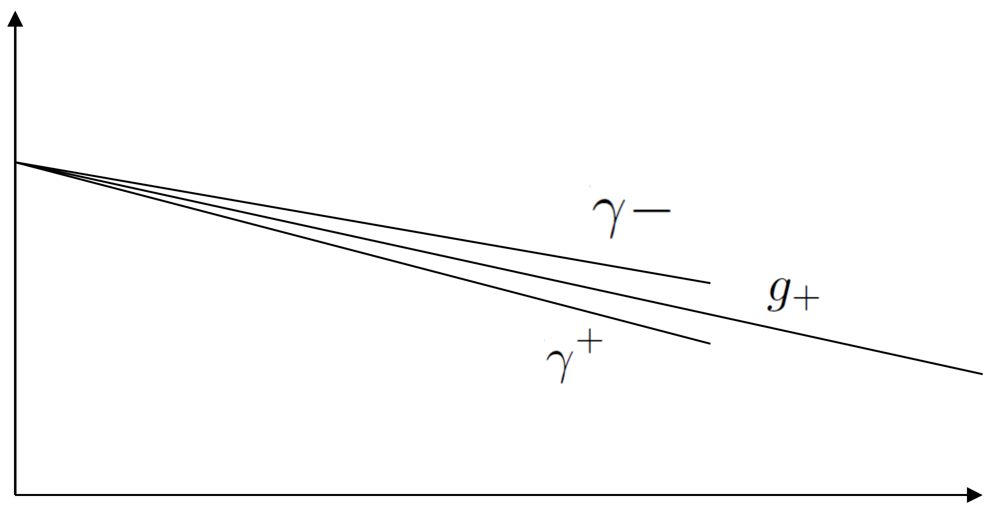
MHD flow + isotropic radiation field

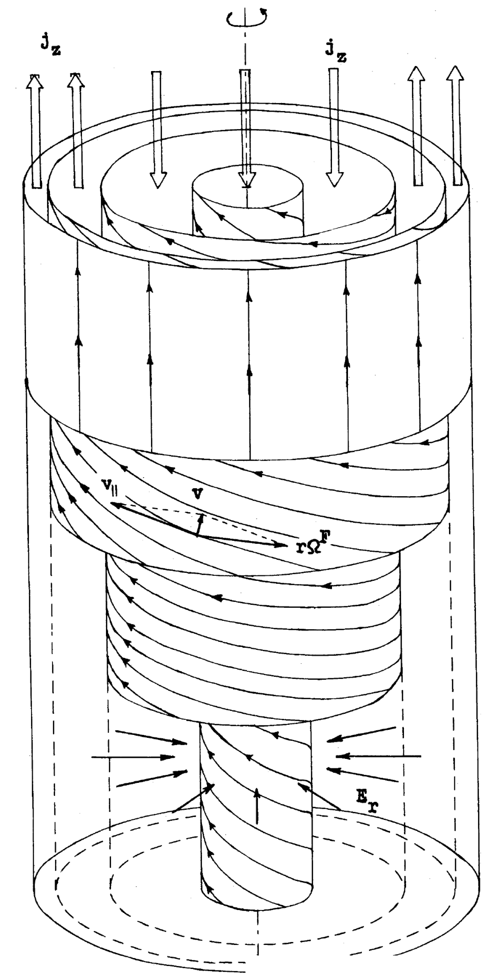
Step IV: Kinetic effects

$$g_+ = \frac{\delta\gamma^+ + \delta\gamma-}{2},$$

$$g_- = \delta\gamma^+ - \delta\gamma-$$

$$\frac{g_-}{g_+} \sim \frac{1}{\lambda\sigma_{\rm M}} \frac{(1+x^2)A}{(1-x^2P_+)^2}\Gamma^3 < 1$$





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

Photon drag

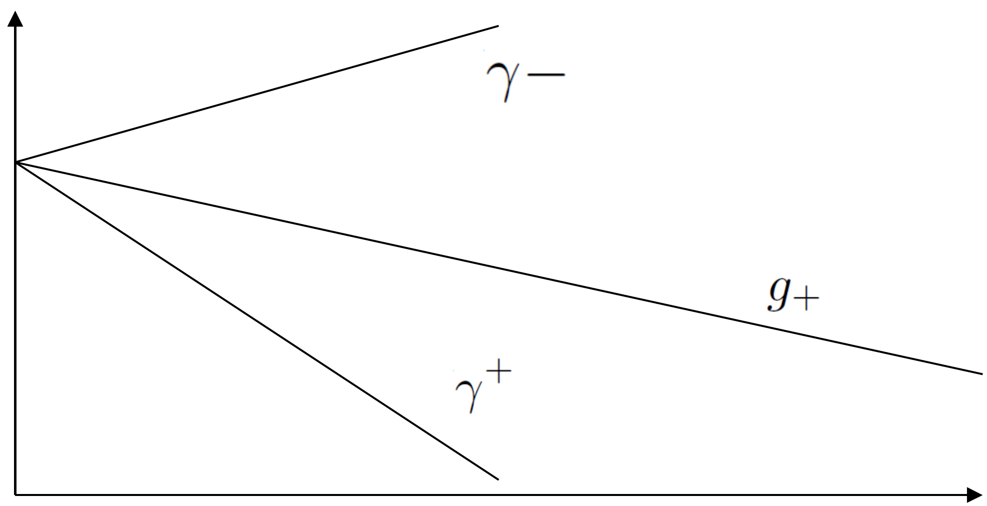
MHD flow + isotropic radiation field

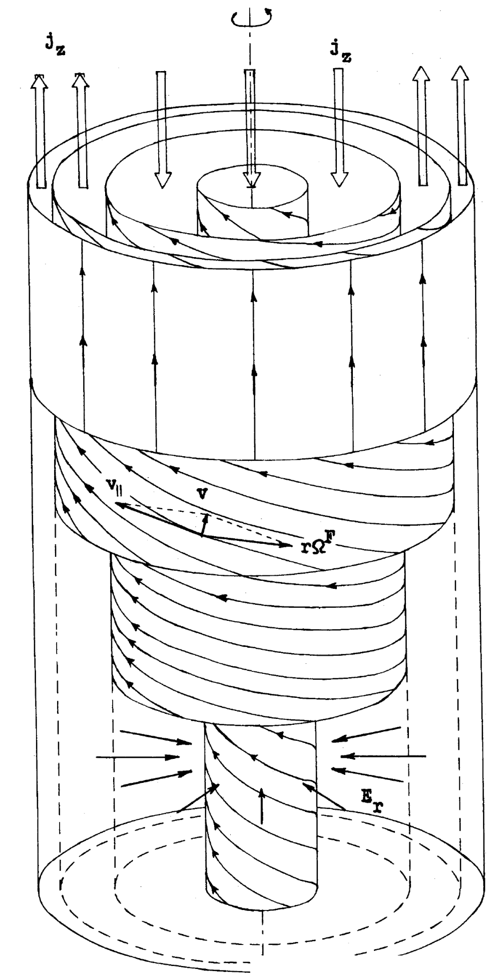
Step IV: Kinetic effects

$$g_+ = \frac{\delta\gamma^+ + \delta\gamma-}{2},$$

$$g_- = \delta\gamma^+ - \delta\gamma-$$

$$\frac{g_-}{g_+} \sim \frac{1}{\lambda\sigma_{\rm M}} \frac{(1+x^2)A}{(1-x^2P_+)^2}\Gamma^3 > 1$$





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

Poster

On the Deceleration of Relativistic Jets in Active Galactic Nuclei II: Particle Loading

VB, E.E.Nokhrina

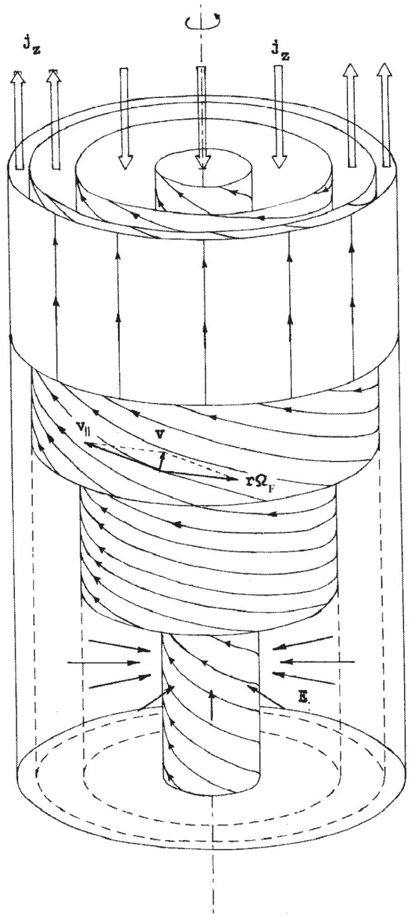
Loading

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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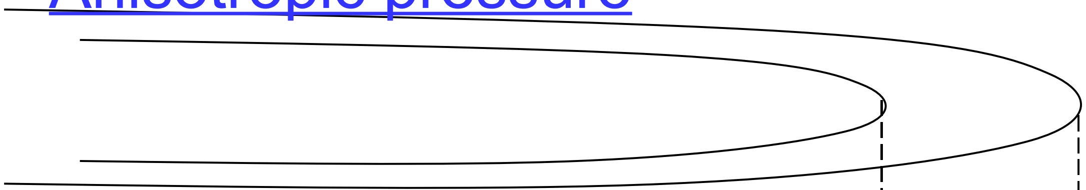
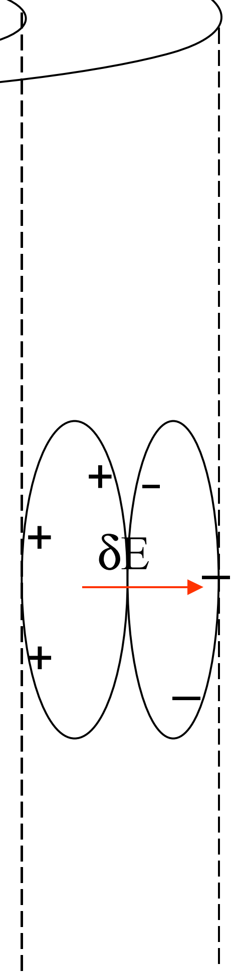
Anisotropic pressure

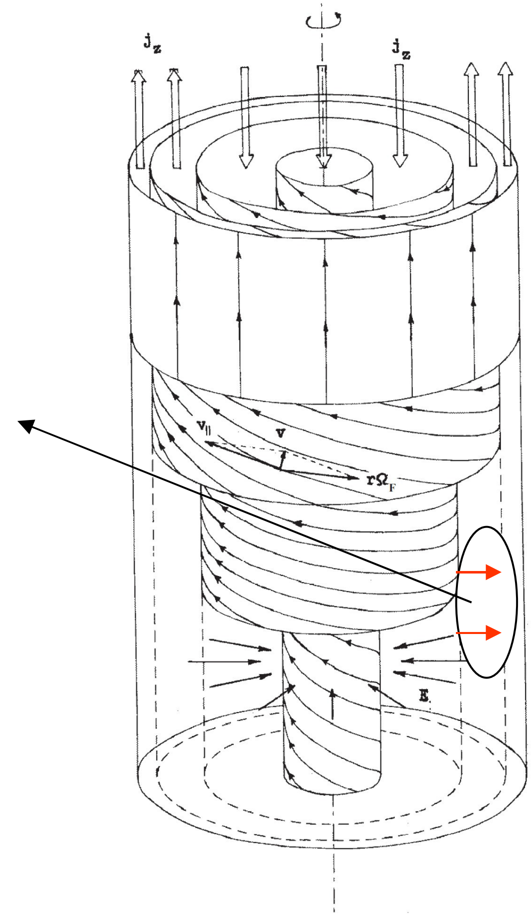


z – moving reference frame

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

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





In this frame

$$\begin{aligned} B_\phi &= B_\varphi/\Gamma, \\ B_z &= B_{\rm p}. \end{aligned}$$

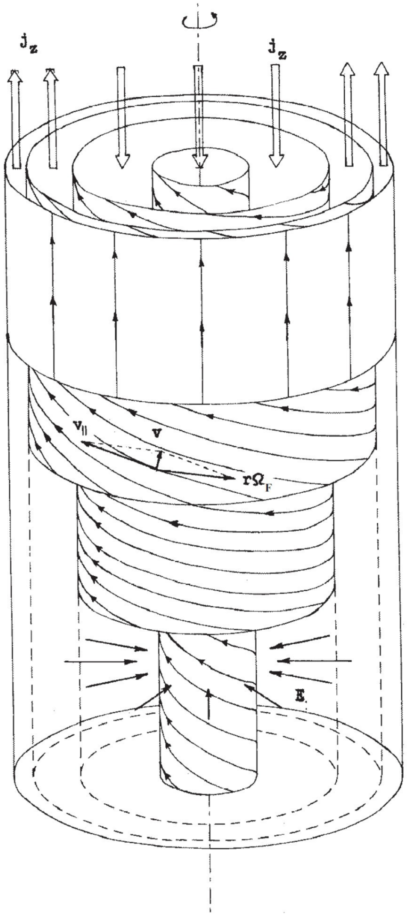
$$\tan\alpha = B_z/B_\phi$$

Loading

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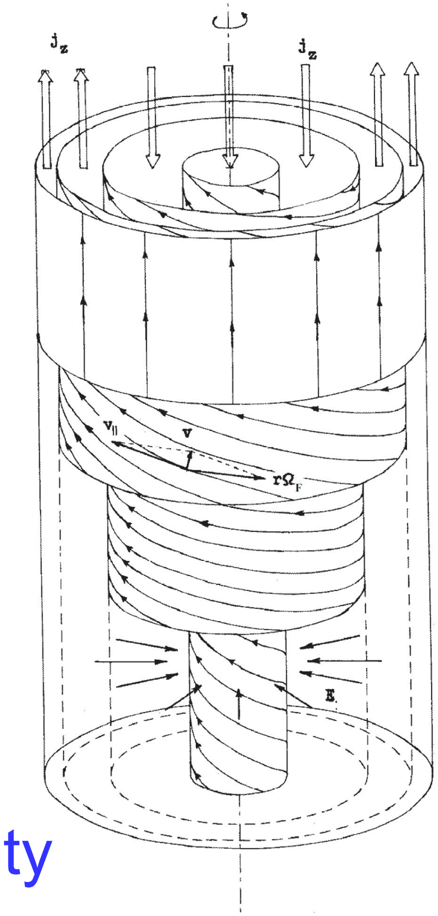
MHD flow + e⁻e⁺ pair creation (at rest)

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

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

- Anisotropic pressure
- 2D – no equi-potentiality



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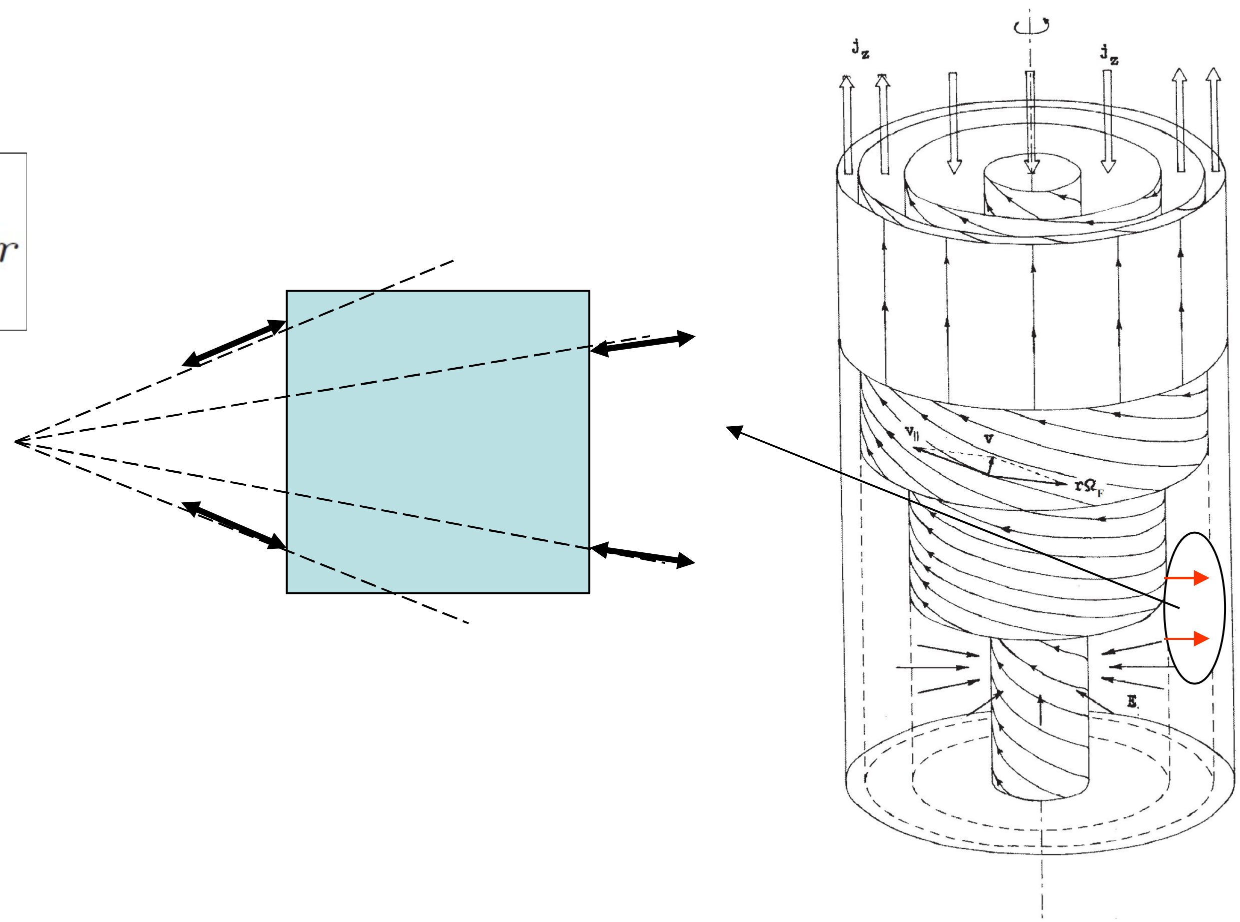
Anisotropic pressure

Radial force

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



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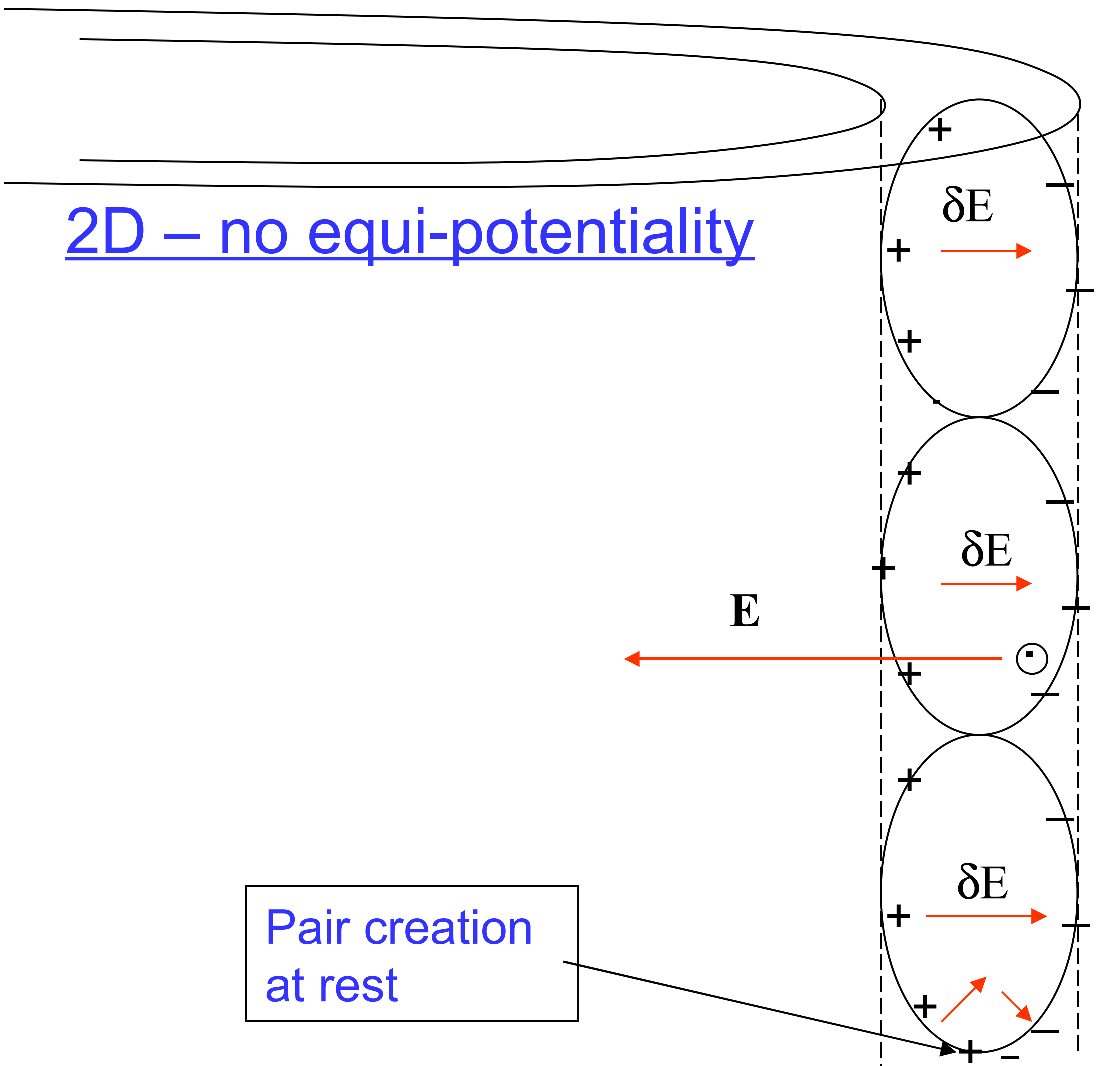
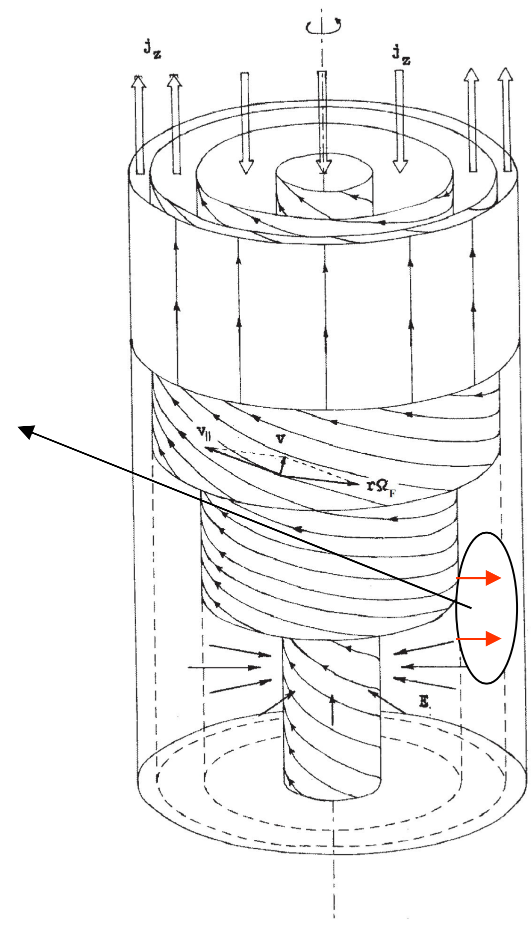
2D – no equi-potentiality



Pair creation
at rest



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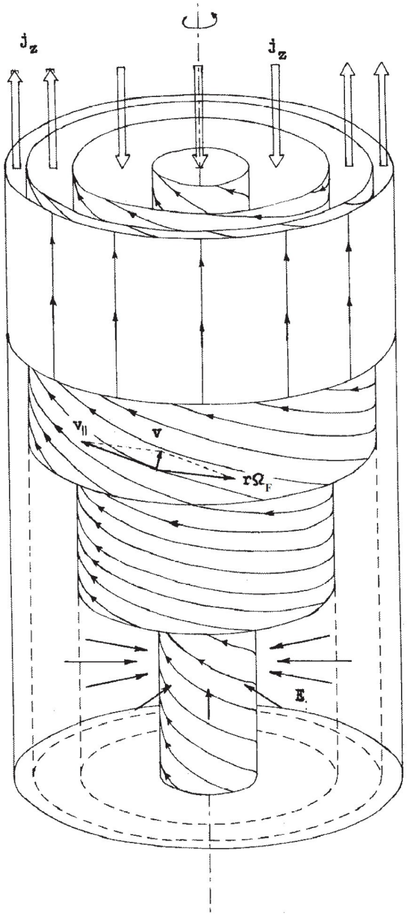
Anisotropic pressure

Rotation in the rz-plane

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

$$\varepsilon_{\rm ld} = n_{\rm ld}^{\rm com} m_{\rm e} c^2 \gamma_{\rm hd},$$
$$P_s = \frac{1}{2} n_{\rm ld}^{\rm com} m_{\rm e} c^2 \gamma_{\rm hd}$$



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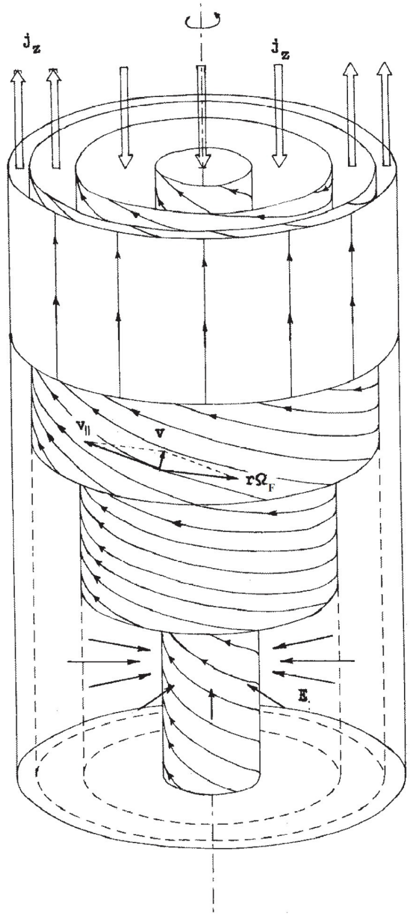
Anisotropic pressure

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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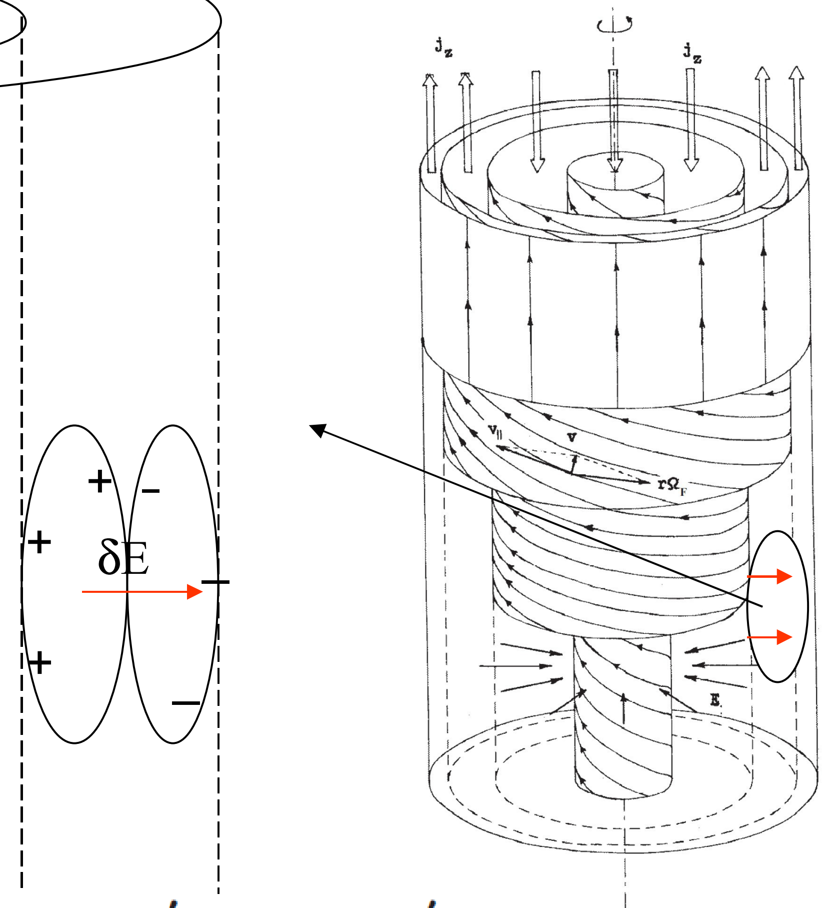
z –moving reference frame

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

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

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

$$< v_r >_t \; = \; \frac{V\Gamma^{-1} \sin\alpha\cos\alpha}{1 - V^2/c^2 \, \sin^2\alpha},$$

$$< v_\phi >_t \; = \; 0,$$

$$< v_z >_t \; = \; \frac{V\cos^2\alpha}{1 - V^2/c^2 \, \sin^2\alpha}$$

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

Mean energy

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

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

Loading

Hydrodynamical motion

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

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

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

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

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~ $\boldsymbol{F}$

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

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 $\delta\mathrm{F} \sim \boldsymbol{F}$

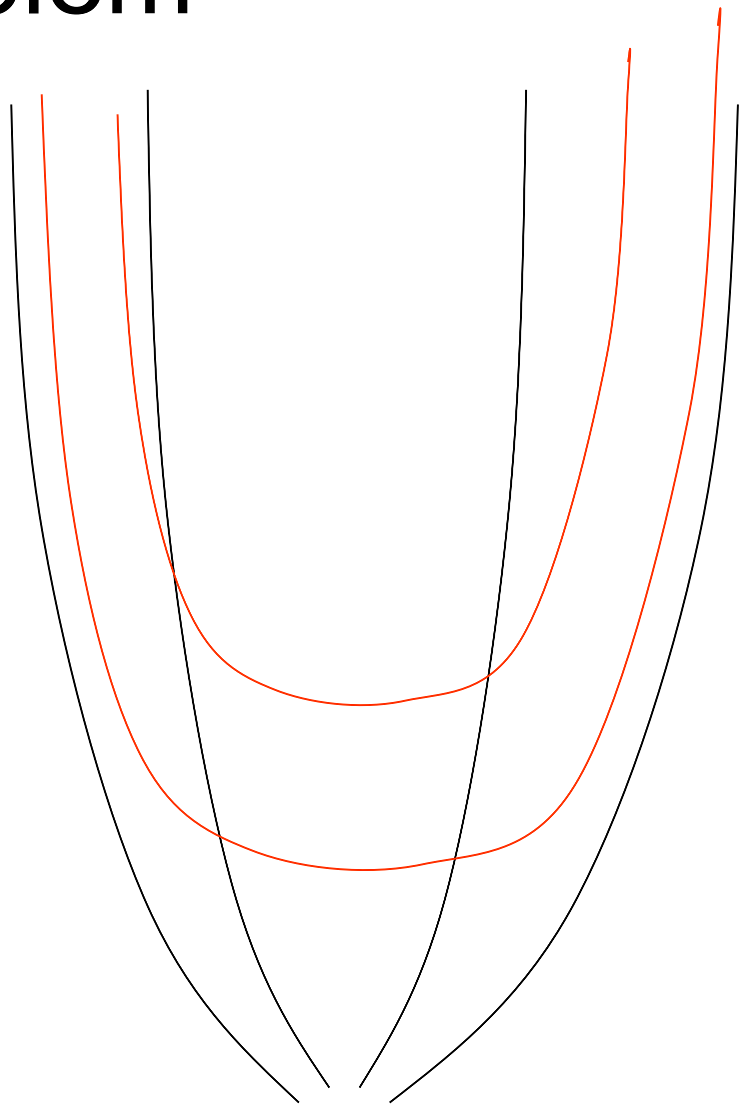
$$\frac{1}{\Gamma^2} = \frac{1}{x_r^2} + \frac{B_\varphi^2 - \mathbf{E}^2}{B_\varphi^2}$$

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

A problem

Longitudinal electric field

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



Conclusion

1. Radiation drag might be a reason for deceleration for small enough magnetization.
2. Disturbances of electric potential AND magnetic surfaces are to be included into consideration.
3. Drag force acting on particles in highly magnetized flow diminishes mainly Poynting flux, not the particle energy.
4. Drag force results in decolimation of magnetic surfaces.

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THANKS AGAIN!