On the Deceleration of Relativistic Jets in Active Galactic Nuclei

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with

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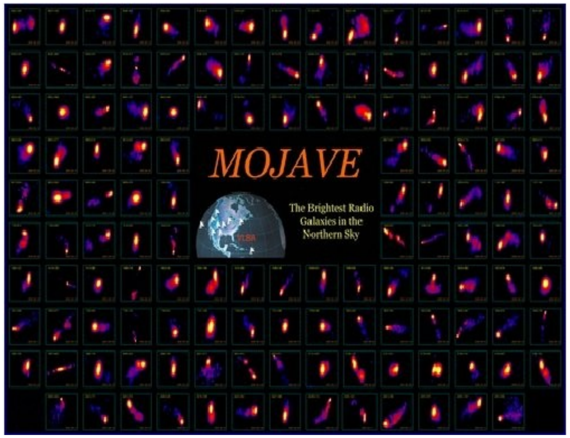
Plan

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

Internal structure – AGN

New possibilities

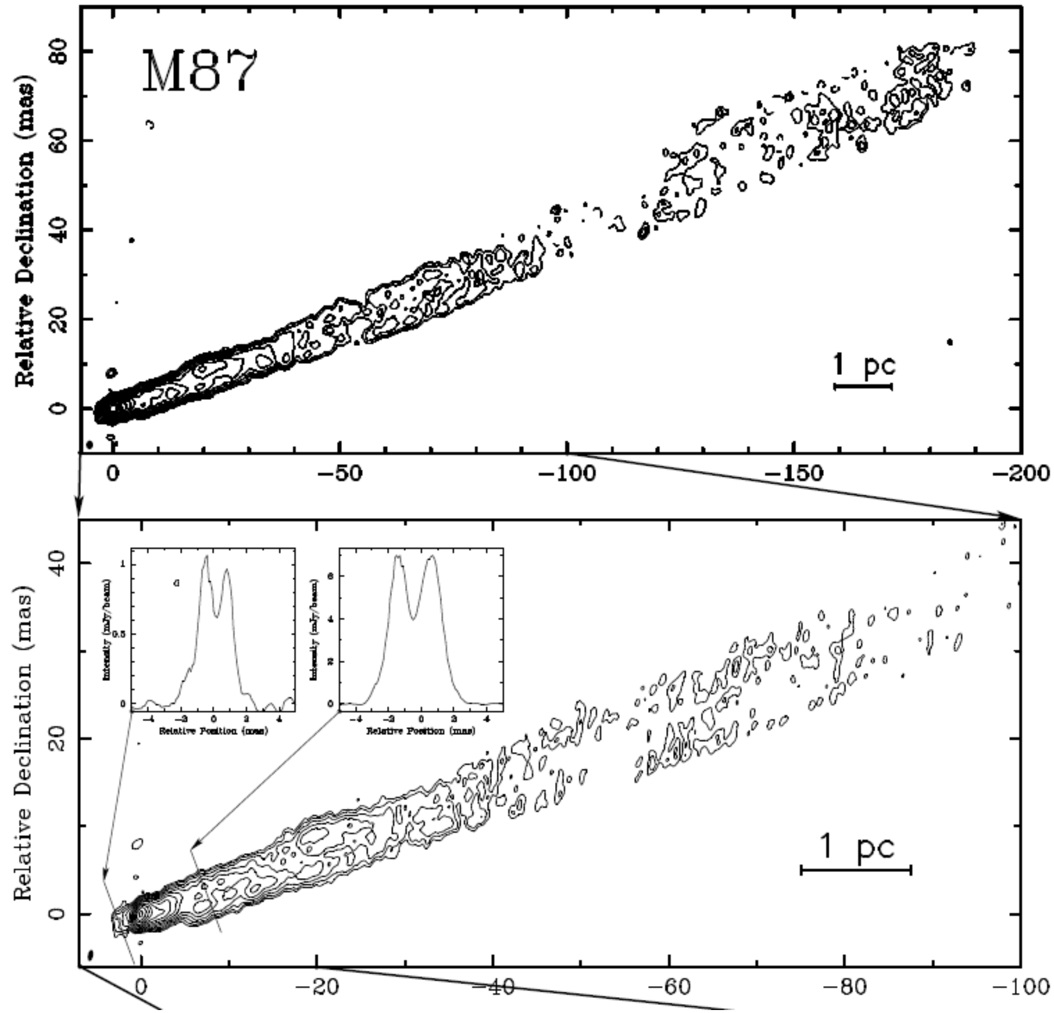


MOJAVE team (time)

Radioastron (base)

Internal structure – AGN

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

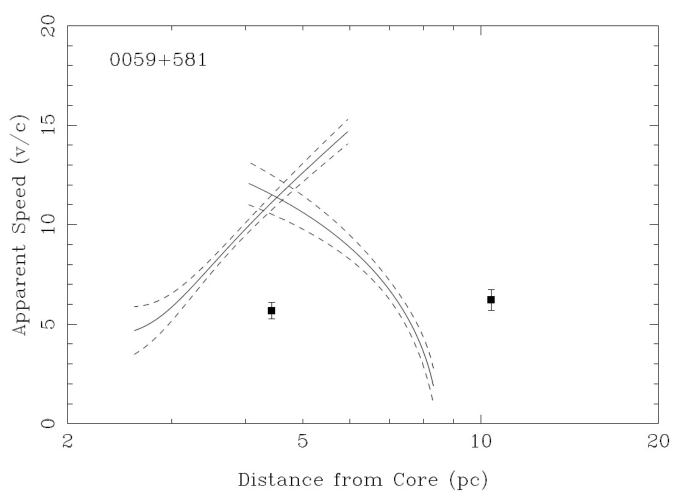


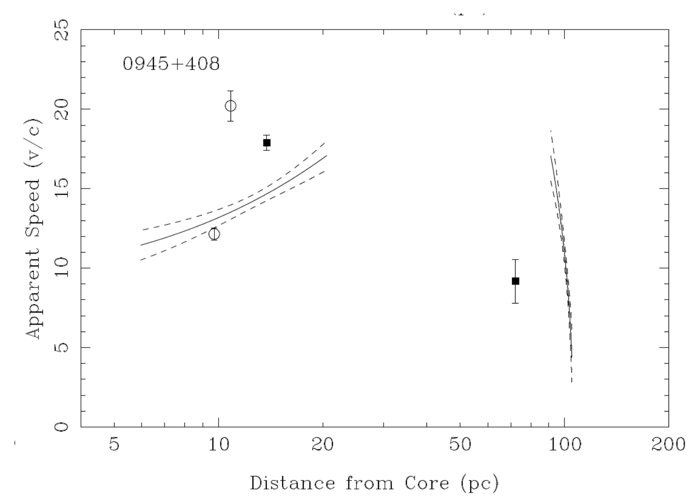
Internal structure – AGN

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

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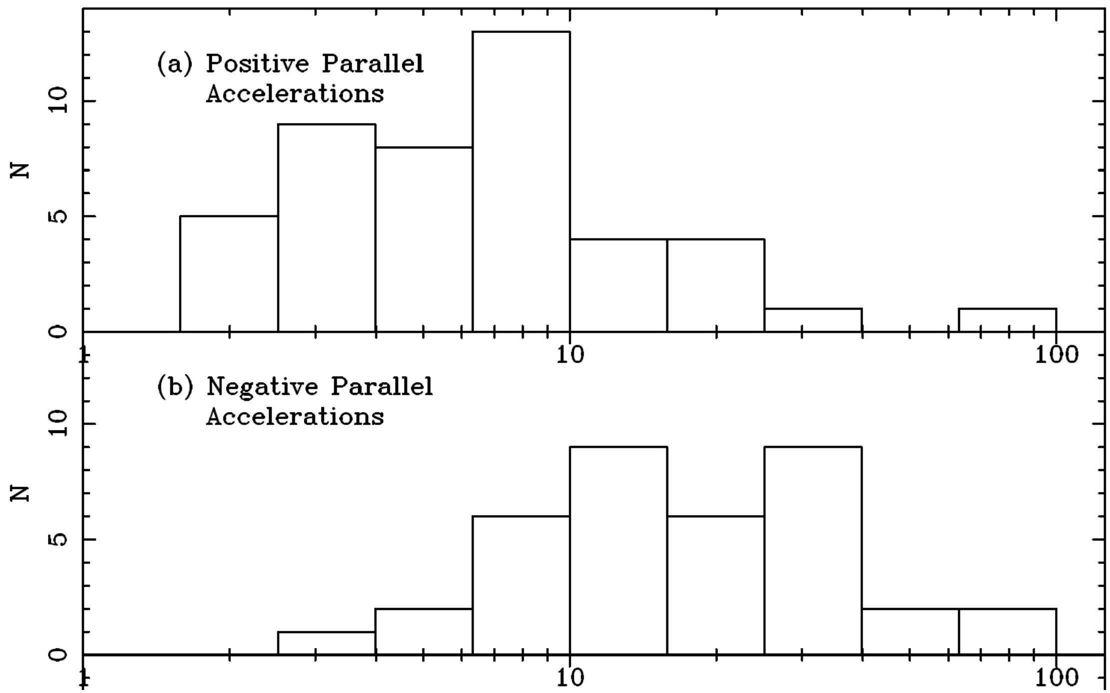


pc (projection)

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

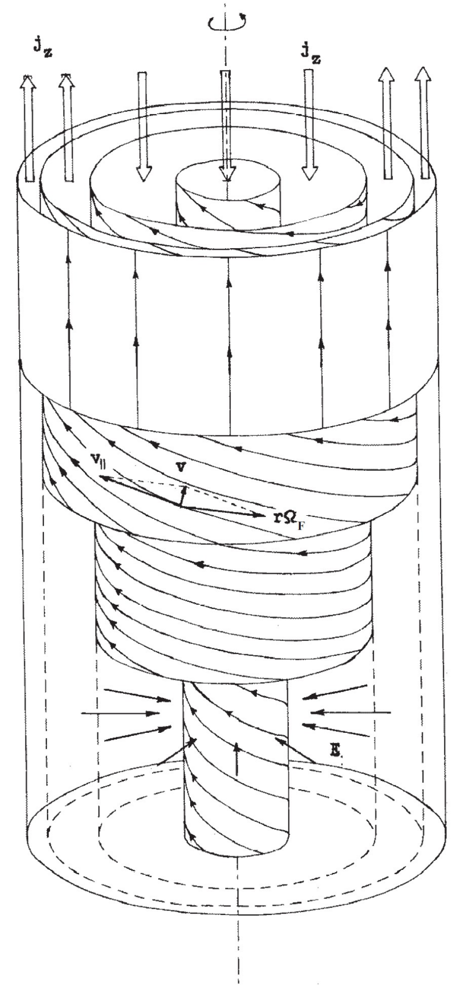
- Multiplicity parameter

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

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

- Total potential drop

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

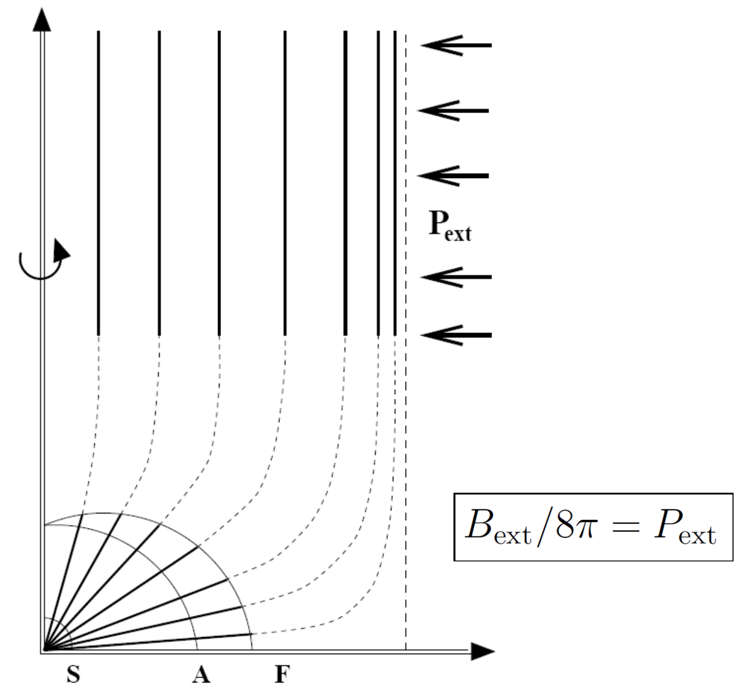


Jets – theory

- It is necessary to include the <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

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

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

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

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

Jets – theory

- Real parameters

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

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

- 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 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)

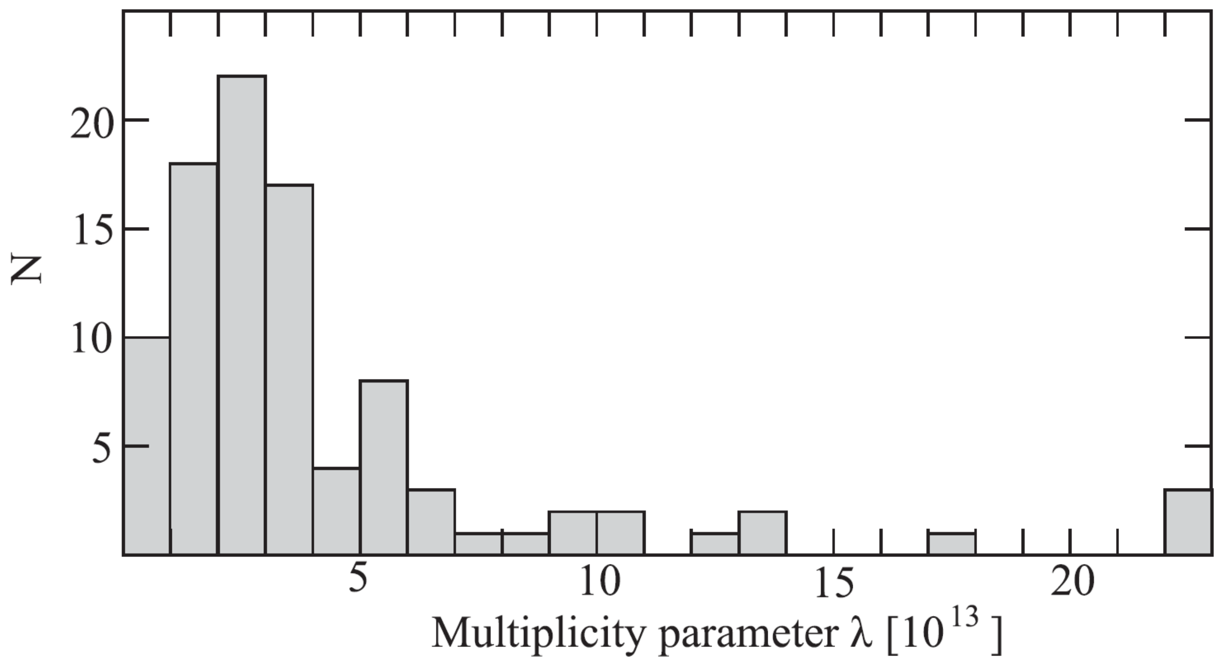


Figure 1. Distributions of the multiplicity parameter λ for the sample of 97 sources. Two objects with $\lambda = 2.8 \times 10^{14}$ and 3.6×10^{14} lie out of the shown range of values.

Core shift and jet parameters

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

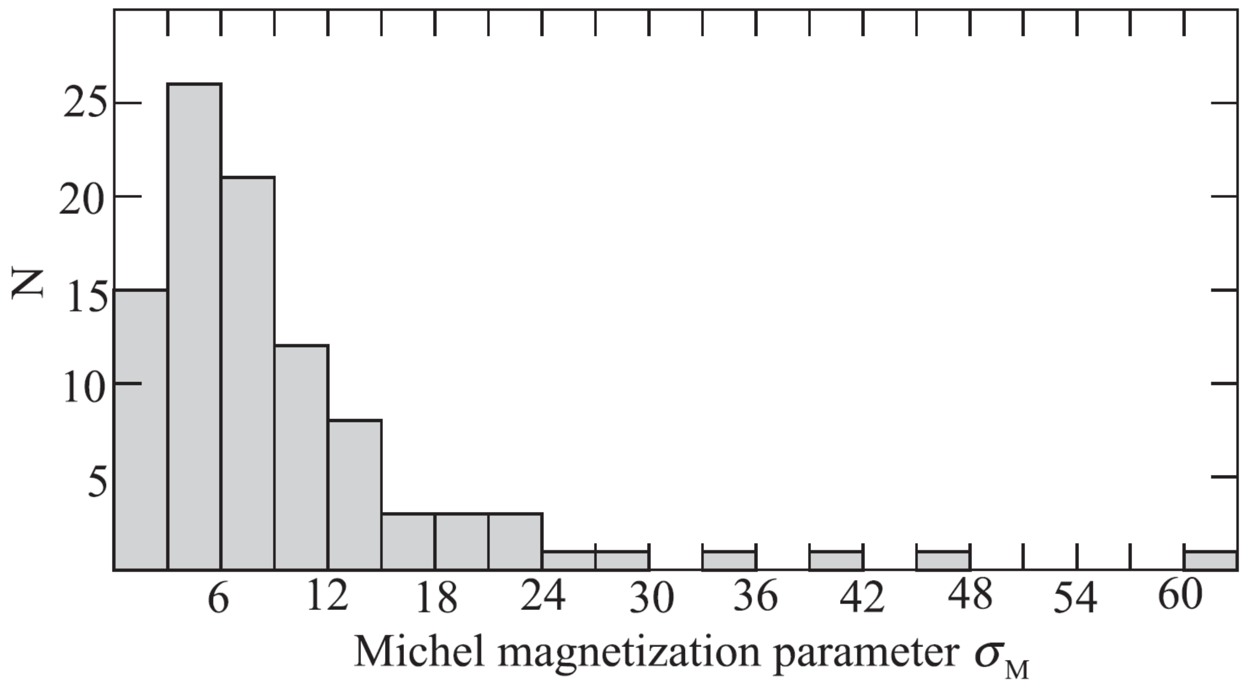


Figure 2. Distributions of the Michel magnetization parameter σ_M for the sample of 97 sources.

Core shift and jet parameters

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

Slow acceleration along the jet

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

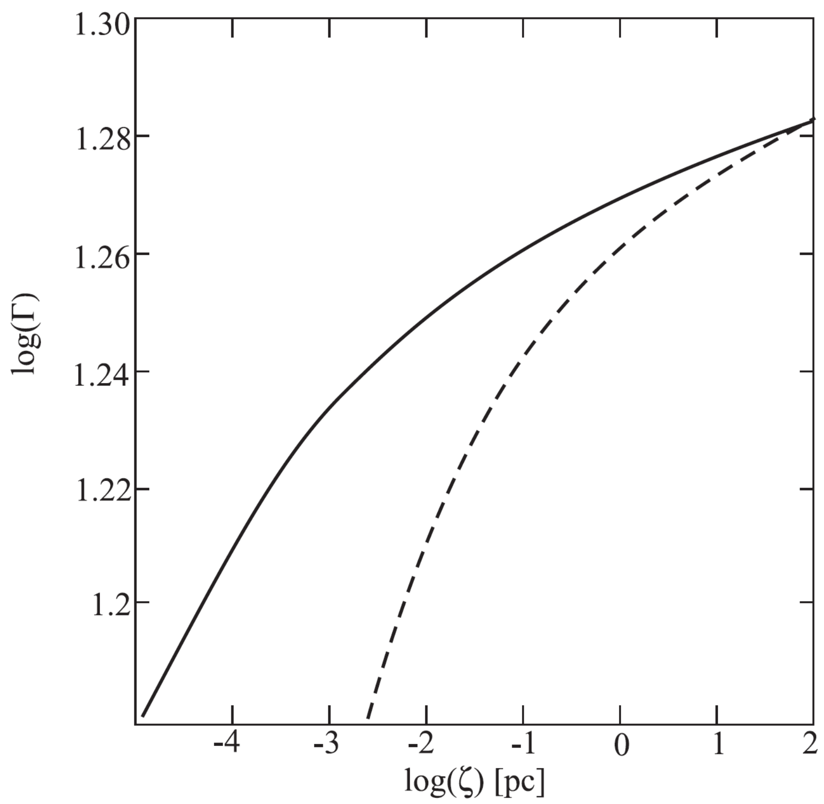
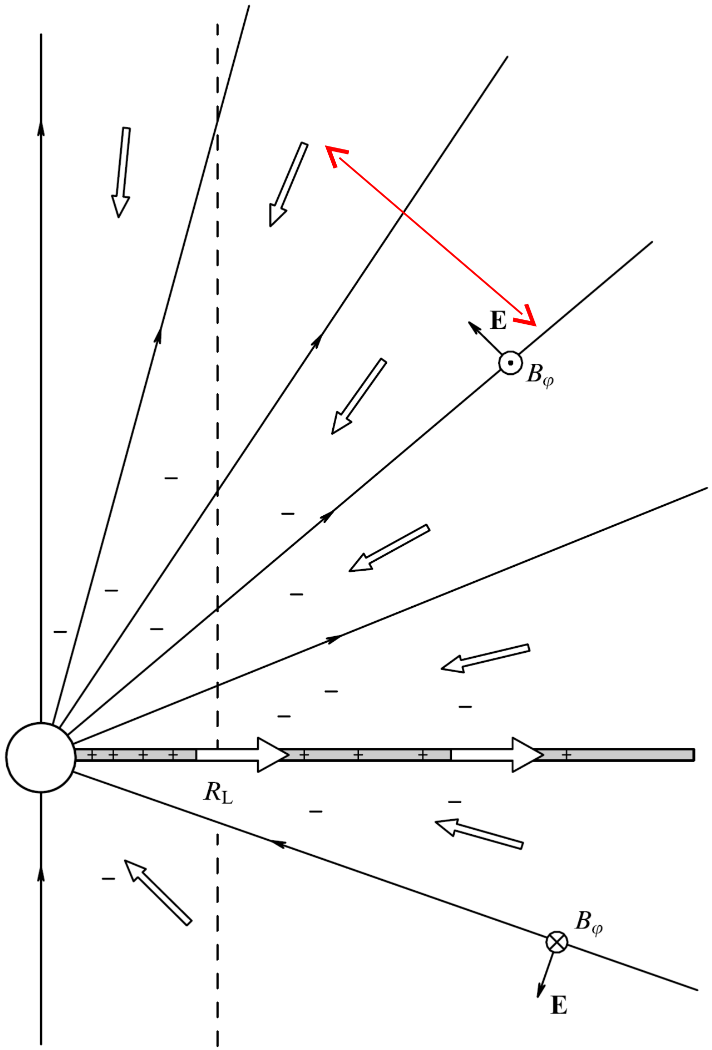


Figure 5. Dependence of Lorentz factor on coordinate along the jet in assumption of $\zeta \propto r_\perp^3$ (solid line) and $\zeta \propto r_\perp^2$ (dashed line) form of the jet.

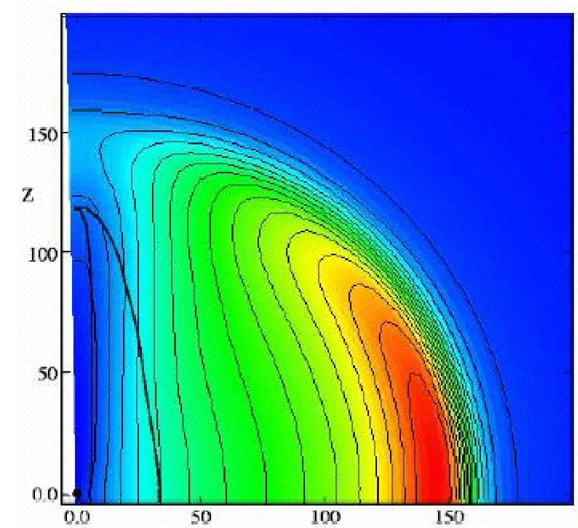
A problem

F.C.Michel (1973)

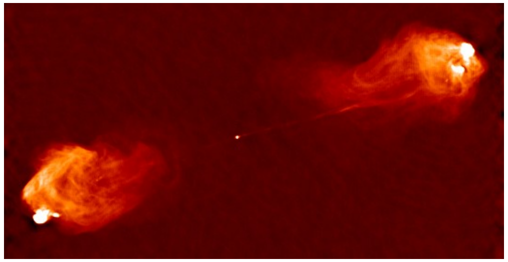


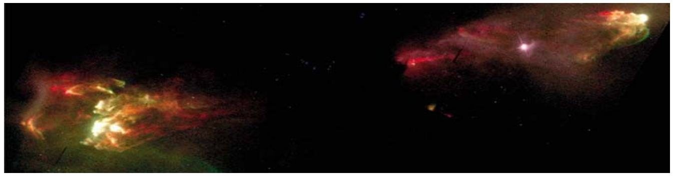
A problem

Switch-on wave, if there is no ambient pressure



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





But what to do if we have it?

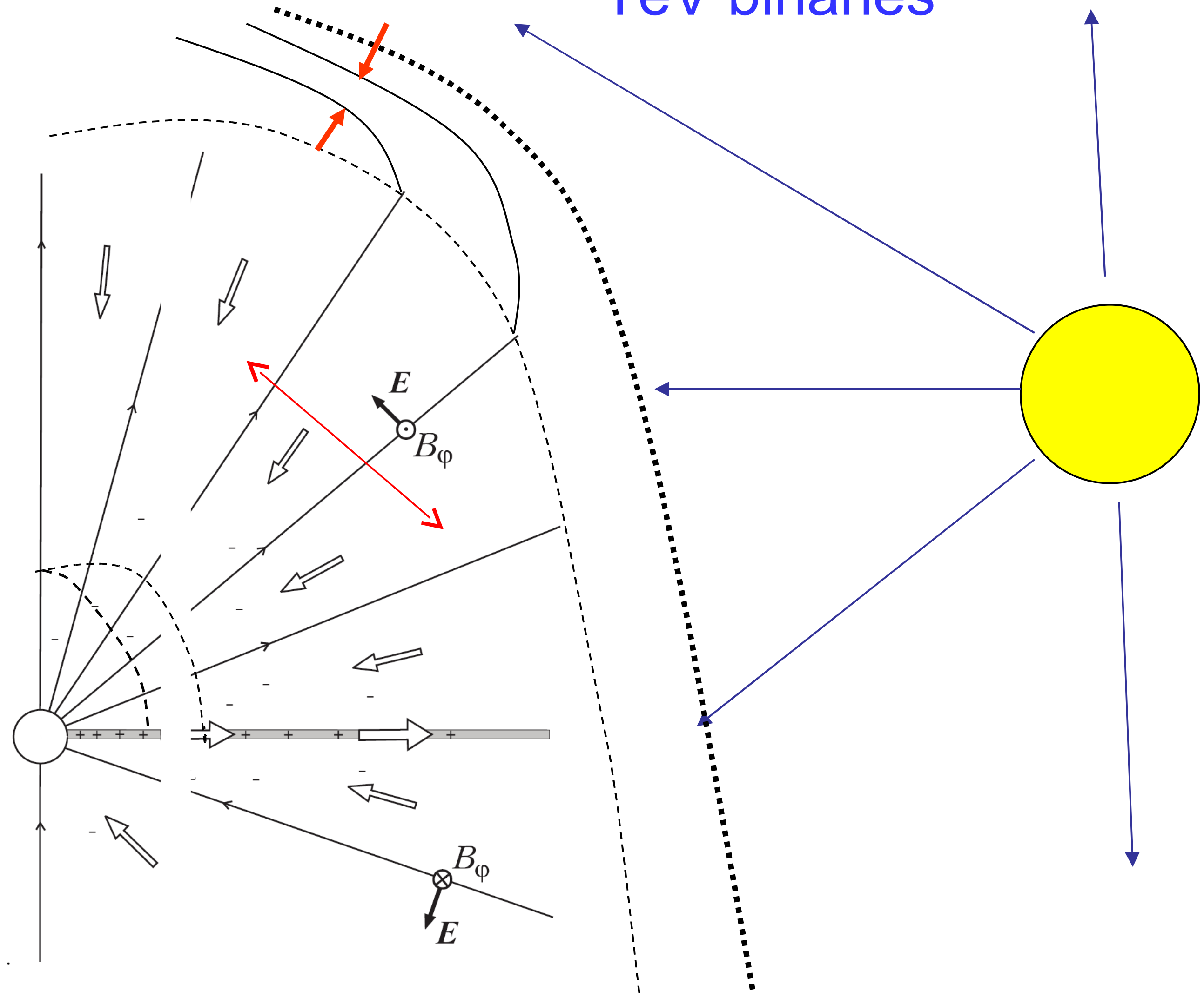
Lobes in AGN

HH objects in YSO

Stellar wind in close binaries

A problem

TeV binaries



A problem

Longitudinal electric field

Magnetically dominated wind → Any disturbance → Longitudinal electric field

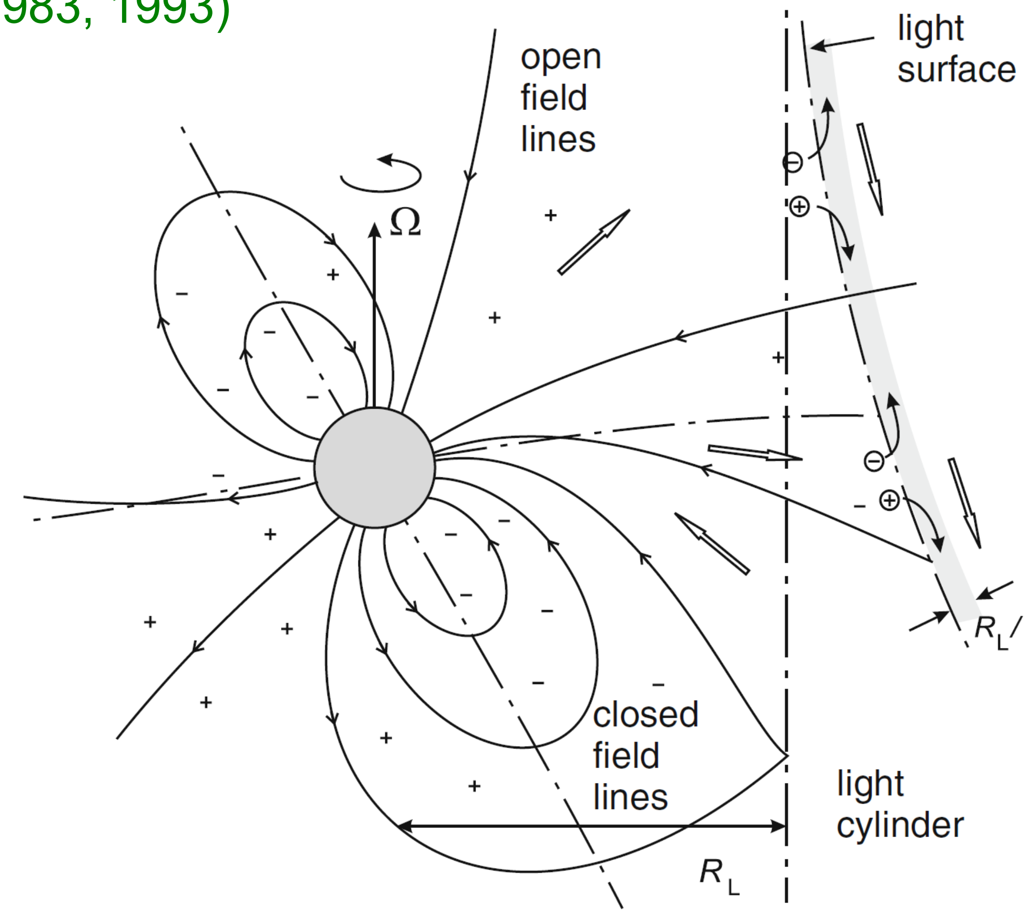
$$\mathrm{E}_{\perp} \longrightarrow E_{||}$$

Statement #1

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

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

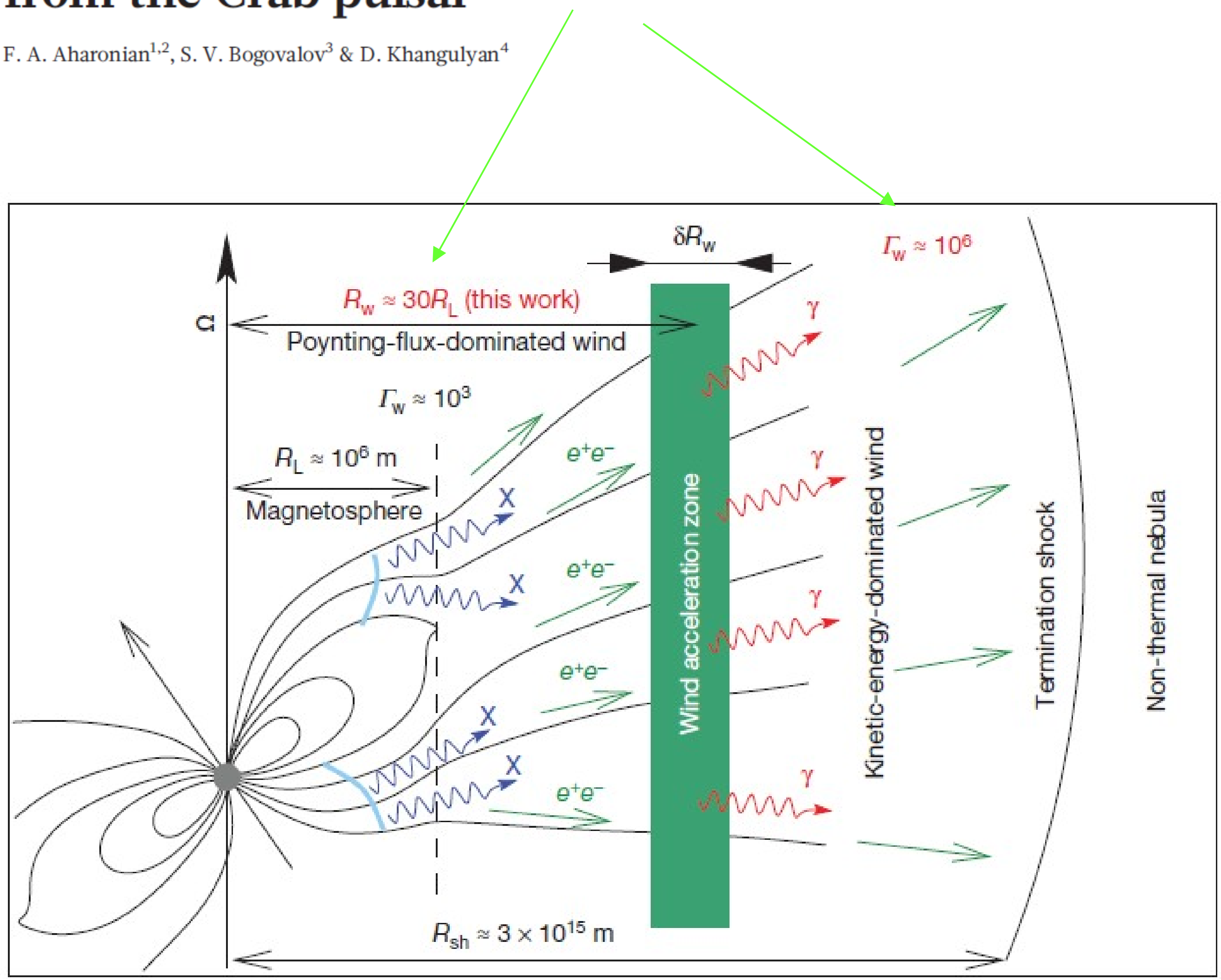
$\Delta r \sim R_L/\lambda$

•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]



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)

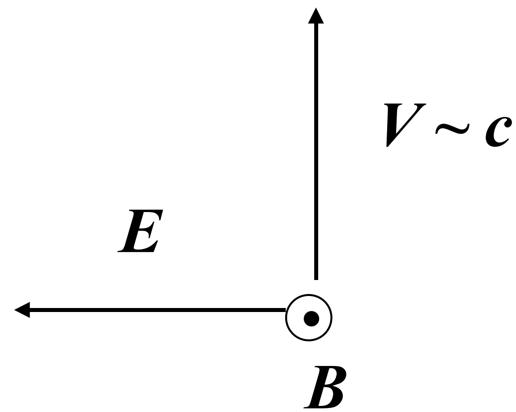
E.V.Derishev, F.Aharonian, V.V.Kocharovsky, Vl.V.Kocharovsky, Phys.Rev.D, **68**, 043003 (2003)

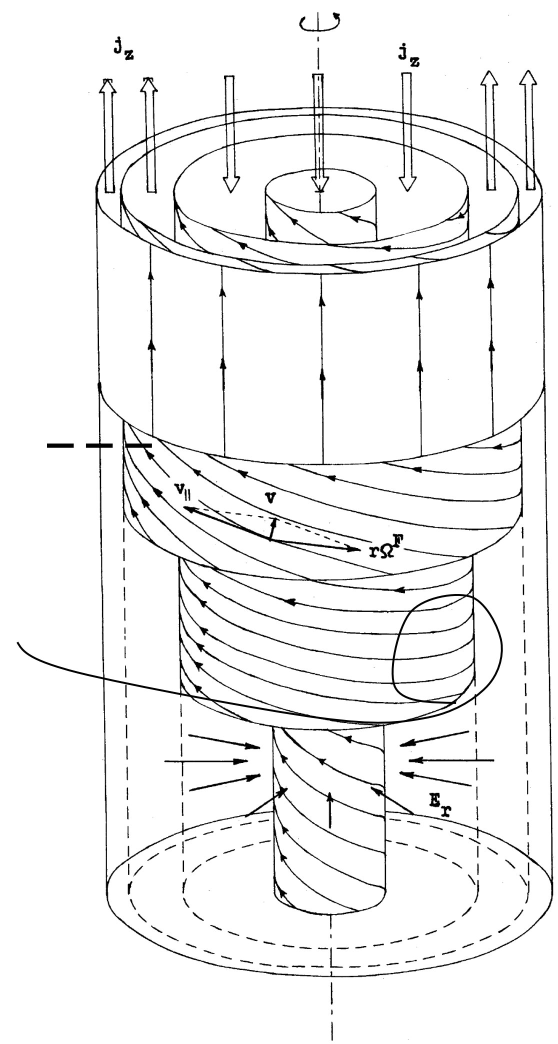
B.Stern, J.Poutanen, MNRAS, 372,1217 (2006)

M.Barkov et al., arXiv:1502.02383

Photon drag

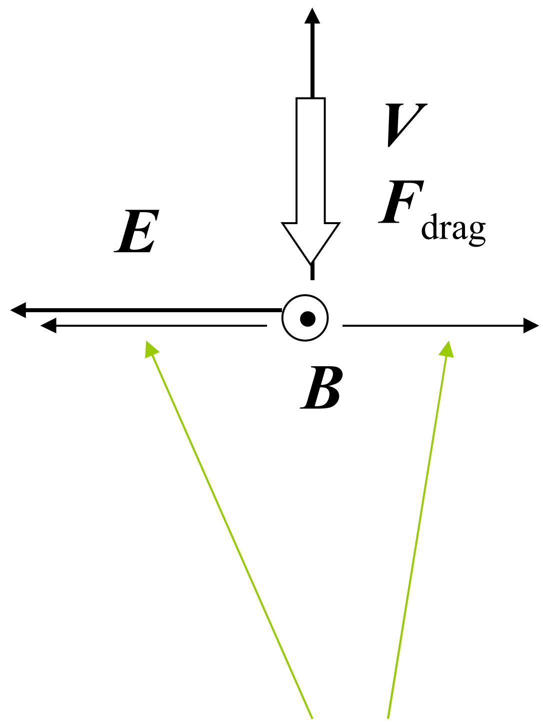
MHD flow + isotropic radiation field





Photon drag

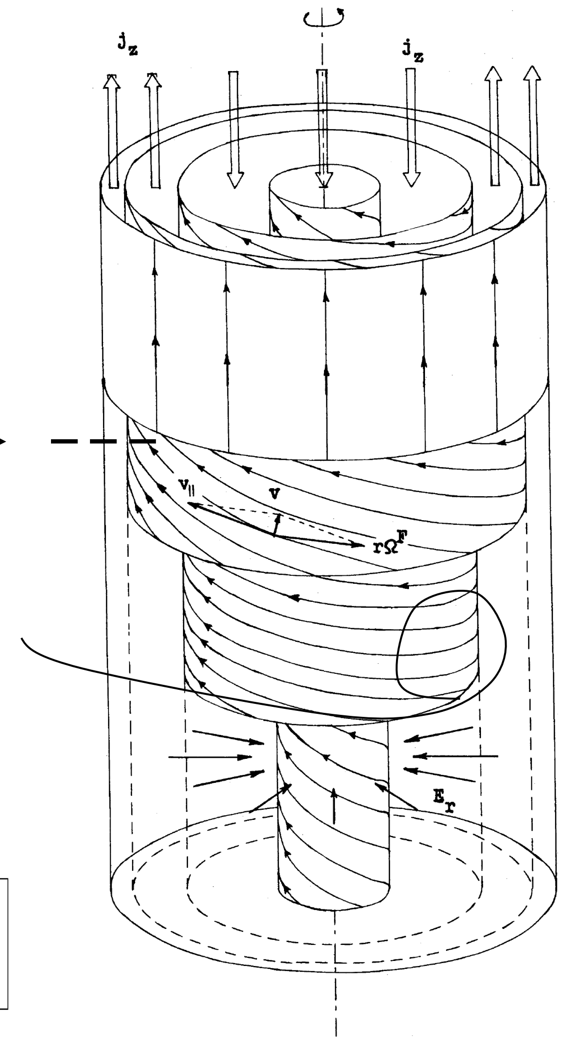
MHD flow + isotropic radiation field



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

MHD flow + isotropic radiation field

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

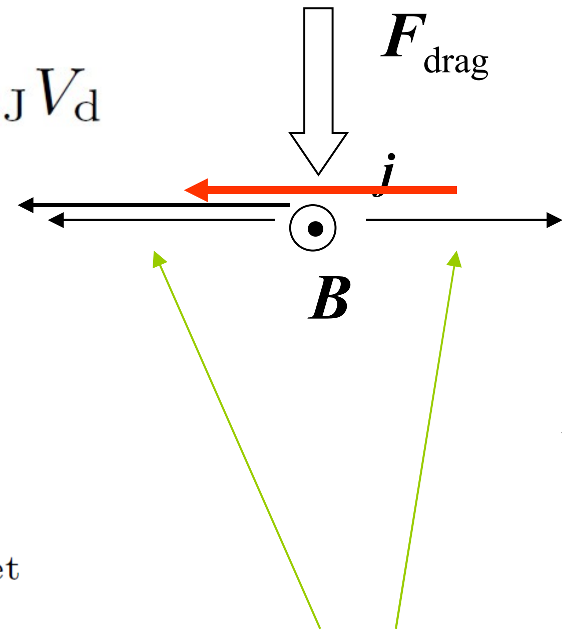
$$\nabla \mathbf{S} = -\mathbf{j}\,\mathbf{E}$$

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

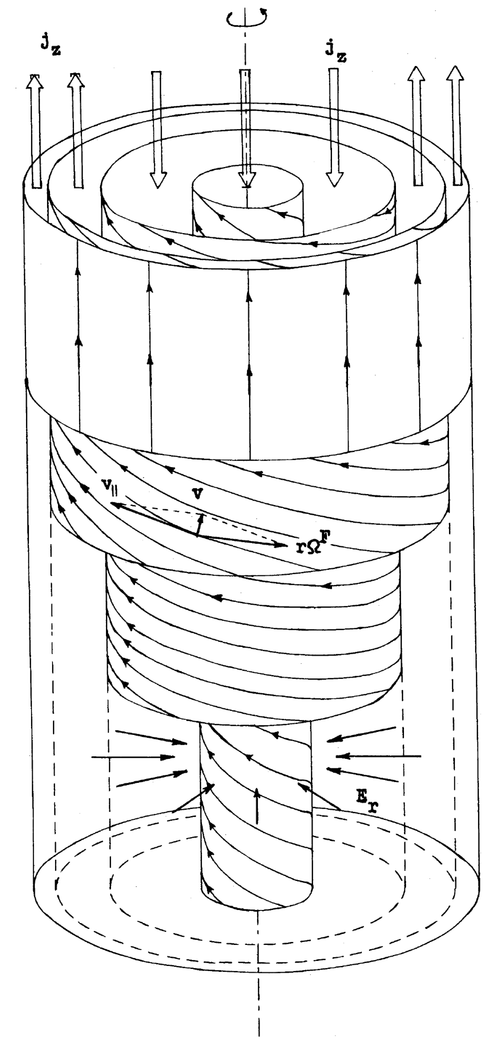
$$B_\varphi / B_z \sim r_{\rm jet}/R_{\rm L}$$

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

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



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



Photon drag

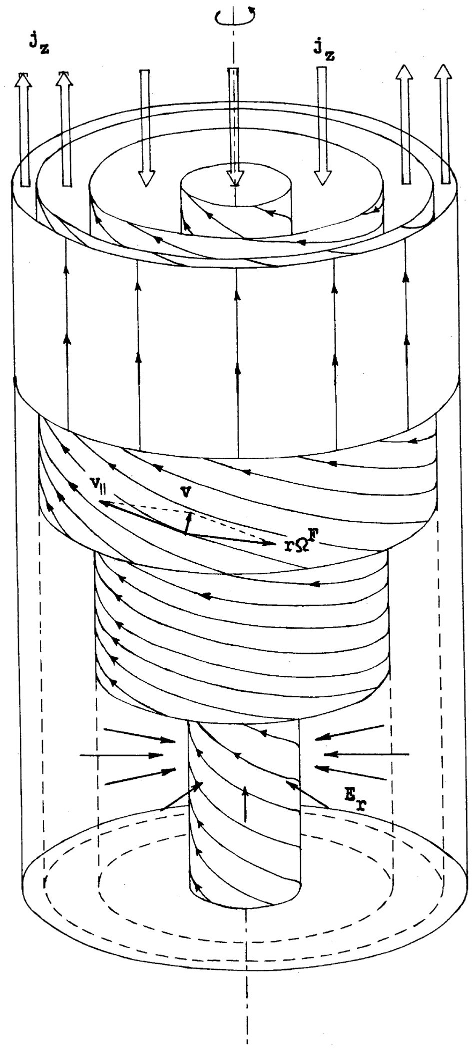
MHD flow + isotropic radiation field

Damping length

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

Appropriate work

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



Photon drag

MHD flow + isotropic radiation field

Zero force-free approximation

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

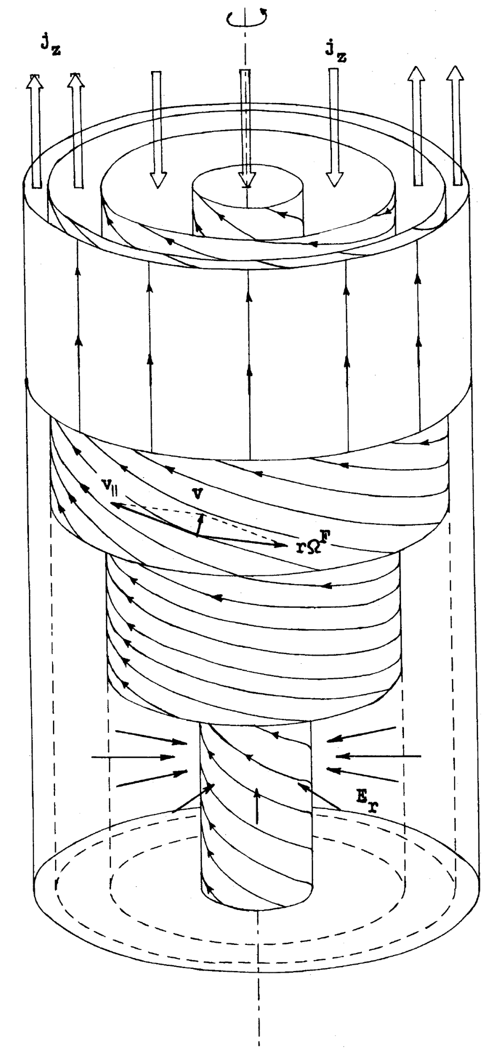
$$\left\{ \begin{array}{lcl} \mathbf{B} & = & \dfrac{\nabla\Psi \times \mathbf{e}_\varphi}{2\pi\varpi} - \dfrac{2I}{c\varpi}\mathbf{e}_\varphi, \\ \mathbf{E} & = & -\dfrac{\Omega_{\rm F}(\Psi)}{2\pi c}\nabla\Psi. \end{array} \right.$$

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

$$B_z^0 = B_0$$

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

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



Photon drag

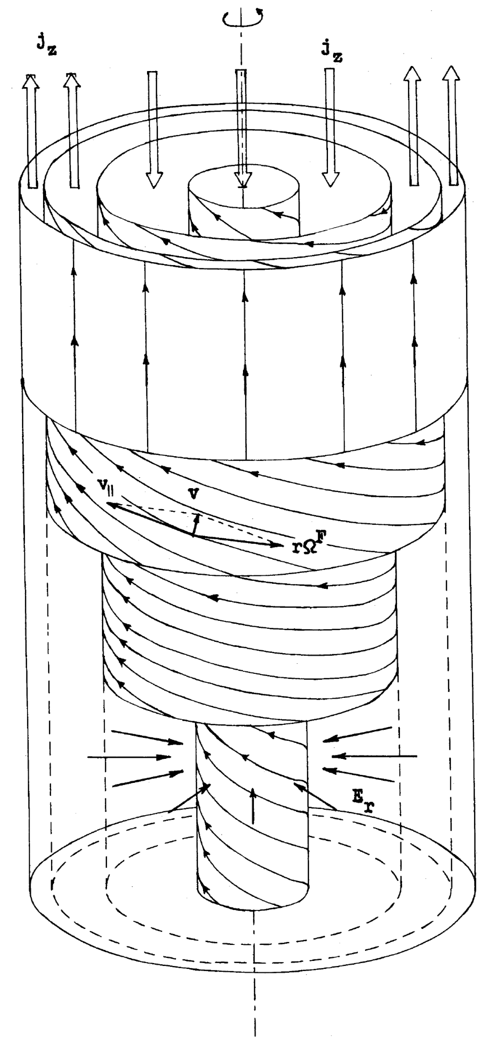
MHD flow + isotropic radiation field

MHD disturbances

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

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

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



Photon drag

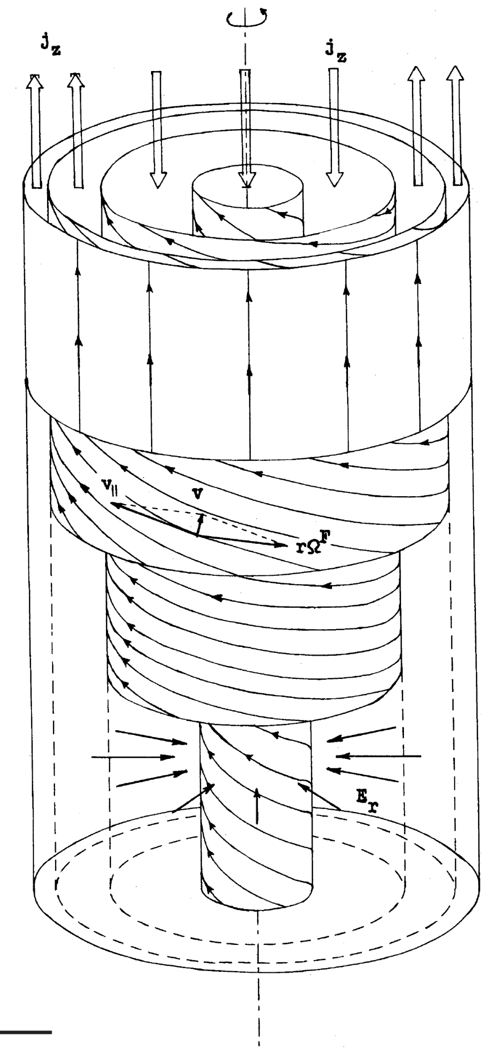
MHD flow + radiation field

How the photon drag affects the MHD flow

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

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

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



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

Photon drag

MHD flow + isotropic radiation field

MHD disturbances + drag

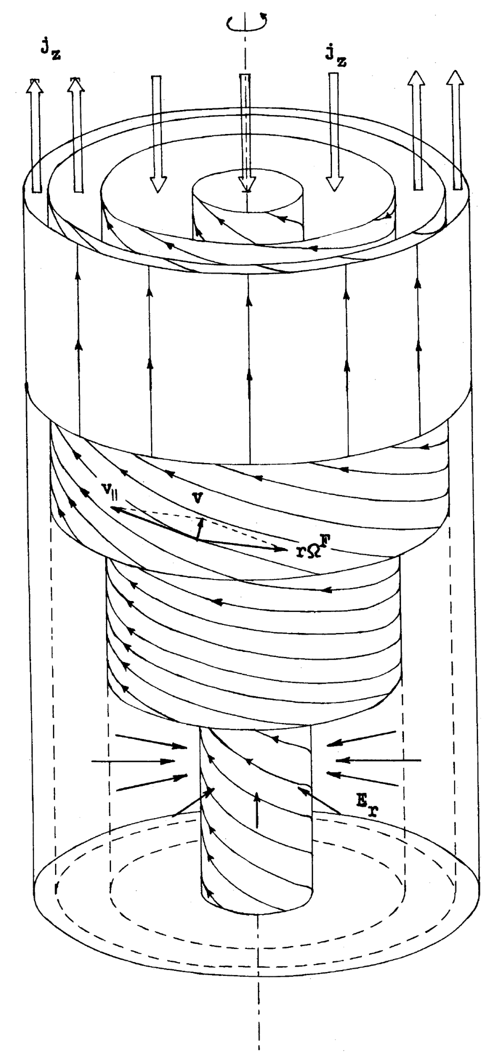
$$
\left\{
\begin{aligned}
&-\frac{1}{r_\perp}\frac{\partial}{\partial r_\perp}(r_\perp^2\zeta) = \\
&2(\eta^+ - \eta^-) - 2\left[(\lambda - K)\,\xi_z^+ - (\lambda + K)\,\xi_z^-\right], \\
&2(\eta^+ - \eta^-) + \frac{1}{r_\perp}\frac{\partial}{\partial r_\perp}\left[r_\perp \frac{\partial}{\partial r_\perp}\left(r_\perp^2\delta\right)\right] + 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_{\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}\left(\xi_r^-\gamma^-\right) = -\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}\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 \\
&+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 \\
&-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.
$$

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

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

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

with N.Zakamska



Photon drag

MHD flow + isotropic radiation field

Step I: MHD disturbances *without* drag

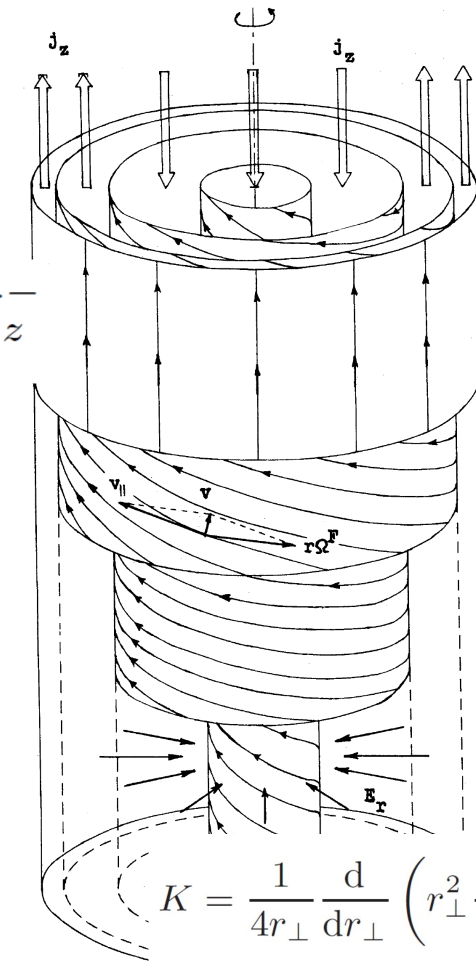
$$
\left\{
\begin{aligned}
-\frac{1}{r_\perp}\frac{\partial}{\partial r_\perp}(r_\perp^2\zeta) &= \\
2(\eta^+-\eta^-) - 2\left[(\lambda-K)\,\xi_z^+ - (\lambda+K)\,\xi_z^-\right]&, \\
2(\eta^+-\eta^-) + \frac{1}{r_\perp}\frac{\partial}{\partial r_\perp}\left[r_\perp\frac{\partial}{\partial r_\perp}\left(r_\perp^2\delta\right)\right] + 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_{\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}\left(\xi_r^-\gamma^-\right) &= -\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}\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 \\
+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 \\
-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.
$$

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

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

$$\xi_r^\pm = 0$$

- Force-free structure remains the exact MHD solution



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

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

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}\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_{\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}\left(\xi_r^-\gamma^-\right) = -\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}\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 \\
& +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 \\
& -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

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

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

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

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

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

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

Photon drag

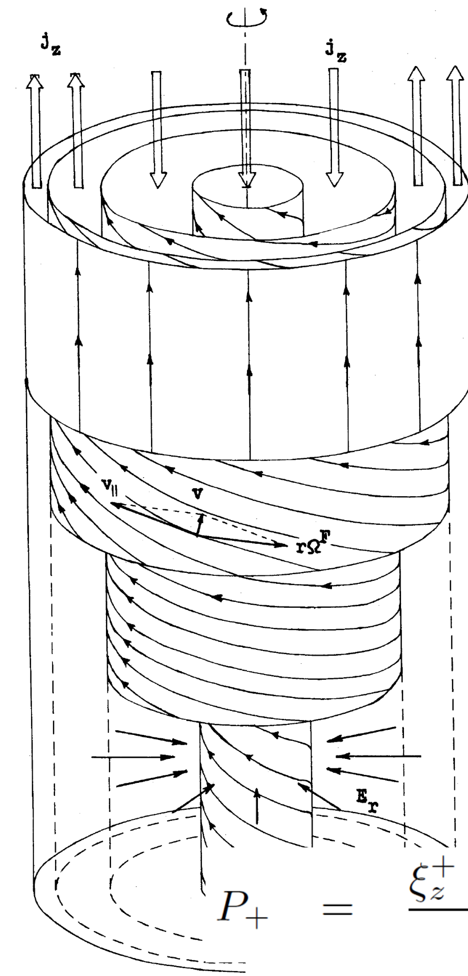
MHD flow + isotropic radiation field

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

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

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

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



$$\frac{\partial\gamma^{\pm}}{\partial z} = -\frac{(1 - x^2 P_+)^2}{(1 + x^2)} F_{\rm d}(\gamma^{\pm})^2$$

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

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

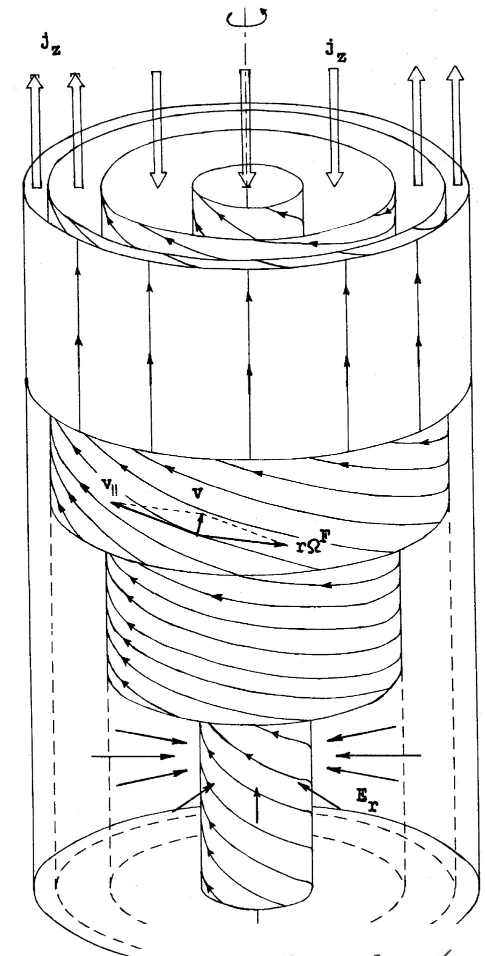
$$F_{\rm d} = \frac{4}{3}\frac{\sigma_{\rm T} U_{\rm iso}}{m_{\rm e}c^2}$$

Photon drag

MHD flow + isotropic radiation field

Step III: Disturbances of electric field and magnetic surfaces

$$2x\frac{\mathrm{d}}{\mathrm{d}x_0}\left[x_0\frac{\mathrm{d}}{\mathrm{d}x_0}D\right] - 2x_0\frac{\mathrm{d}}{\mathrm{d}x_0}\left[\frac{1}{x_0}\frac{\mathrm{d}}{\mathrm{d}x_0}\left(\frac{\Omega_0}{\Omega_\mathrm{F}}D\right)\right] +$$
$$8Kx_0\frac{\mathrm{d}}{\mathrm{d}x_0}D - 2x\frac{\mathrm{d}}{\mathrm{d}x_0}\left[4K\frac{x_0(x^2+1-x^2P_+)}{x(1+x^2)}D\right] +$$
$$\frac{32K^2xx_0P_+(x^2+1-x^2P_+)}{(1+x^2)(1-x^2P_+)}D - \frac{32K^2xx_0}{(1-x^2P_+)}D -$$
$$\frac{32K^2}{(1+x^2)}D = 2x\frac{\mathrm{d}}{\mathrm{d}x_0}\left[x_0^2\mathcal{G}\right] - 8Kx_0^2\mathcal{G}$$



$$D = x_0^2\delta$$

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

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

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

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

Photon drag

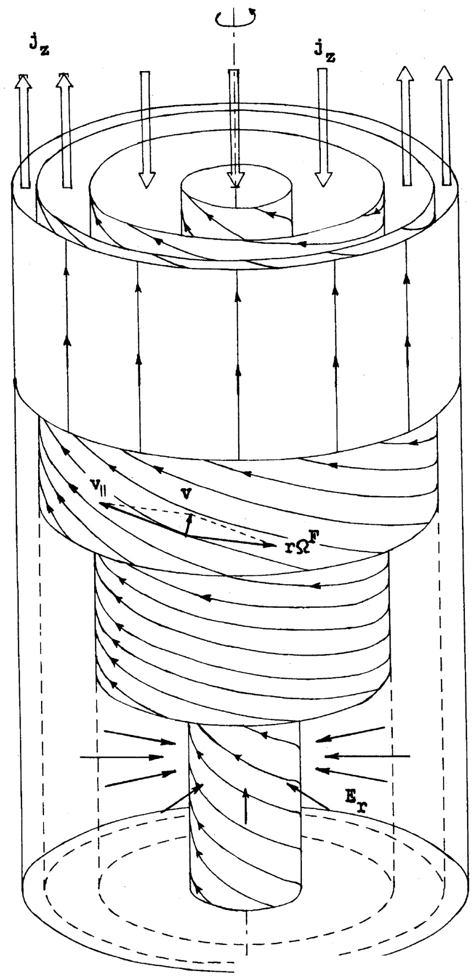
MHD flow + isotropic radiation field

Step III: Disturbances of electric field and magnetic surfaces

$$\delta \sim \frac{A}{\sigma_{\rm M}}\Gamma^2(F_{\rm d} z)$$

$$L_{\rm dr} \sim \frac{\sigma_{\rm M}}{\Gamma^2 F_{\rm d}}$$

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



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

Photon drag

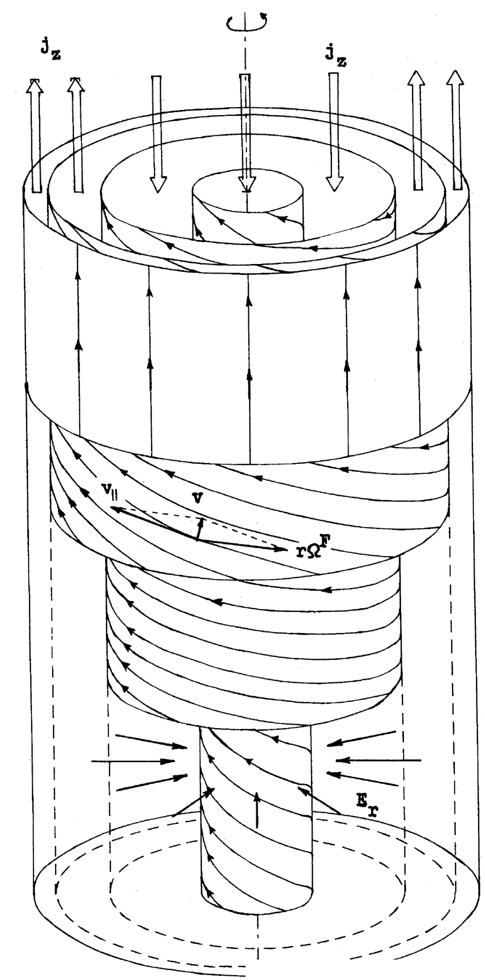
MHD flow + isotropic radiation field

Step III: Disturbances of electric field and magnetic surfaces

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

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

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



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

Poster

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

VB, E.E.Nokhrina

Conclusion

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

THANKS AGAIN!