Physics of Poynting dominated jets

Yuri Lyubarsky

Ben-Gurion University
Beer-Sheva, Israel

Poynting dominated jets.
What do we want to know?

1. What are the conditions for acceleration and collimation?

2. What is the final collimation angle?

3. Where and how the EM energy is released?
   Conversion to the kinetic energy via gradual acceleration?
   Or to the thermal and radiation energy via dissipation?

4. Are they stable? What is the role of possible MHD instabilities?

Intimate connection between collimation and acceleration

Without external confinement, the flow is nearly radial; the acceleration stops at an early stage (Tomimatsu 94; Beskin et al 98)

Jet confined by the external pressure: the spatial distribution of the confining pressure determines the shape of the flow boundary and the acceleration rate (Tchekhovskoy et al 08,09; Komissarov et al 09; L 09,10).

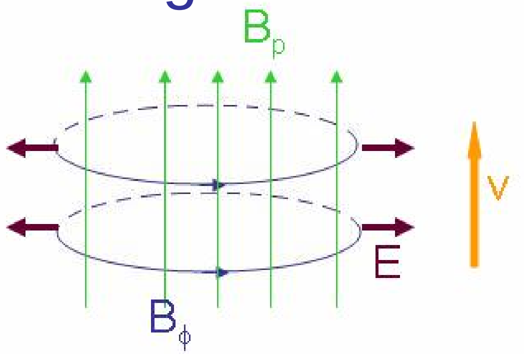
In accreting systems, the relativistic outflows from the central engine could be confined by the (generally magnetized) wind from the outer parts of the accretion disk. In GRBs, a relativistic jet from the collapsing core is confined by the stellar envelope.

Collimation vs acceleration
1. Equilibrium jet

Transverse force balance in cylindrical configuration.

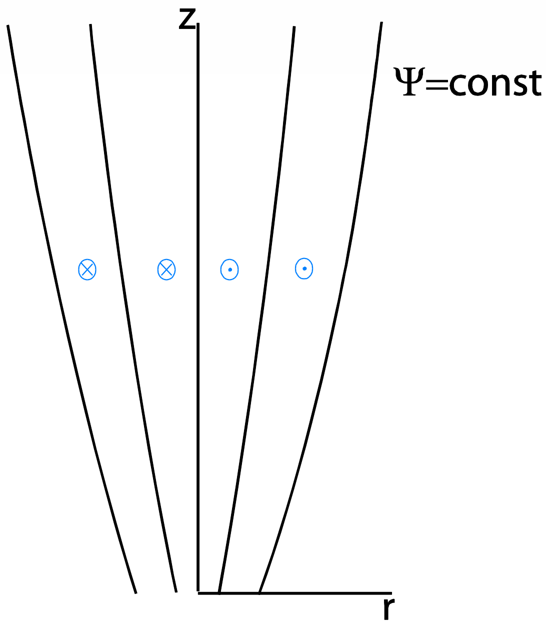
In the comoving frame, $B'\varphi \sim B'p$

In the lab frame, $B\varphi = \gamma B'\varphi \sim \gamma B'p = \gamma Bp$



cylindrical equilibrium at any z

At $r > R_L$, each revolution of the source adds to the wind one more magnetic loop: $B_{\varphi} \approx (r\Omega/c)B_p$

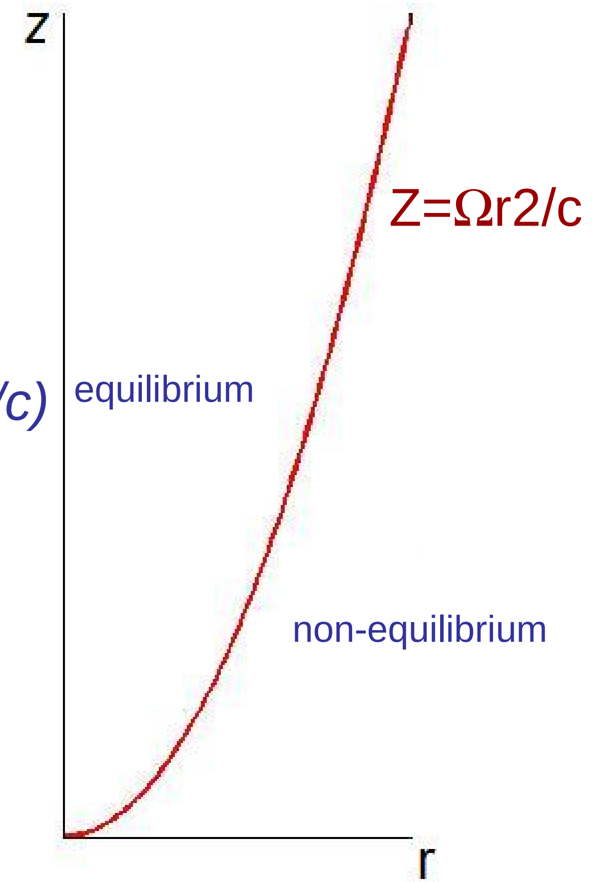


$\gamma \sim r\Omega/c$

The jet is accelerated when expands

Collimation vs acceleration
1. Equilibrium jet (cont)

The flow settles into an equilibrium configuration provided a signal crosses the jet while z varies less than 2 times (strong causality).



(proper propagation time, *z/cγ*) > (light crossing time, *r/c*)

$$z > r\gamma \sim \frac{\Omega r^2}{c}$$

$$\Theta = \frac{dr}{dz} \sim \frac{r}{z}$$

$\Theta\gamma<1$

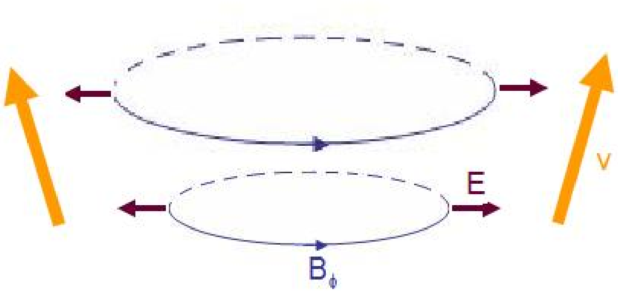
Expanding equilibrium jets are accelerated,
$\gamma \sim \Theta r/c$, up to $\gamma \sim \gamma_{max}$; $\sigma \sim 1$

γmax>>1 - the Lorentz factor achieved when and if the Poynting flux is completely transformed into the kinetic energy

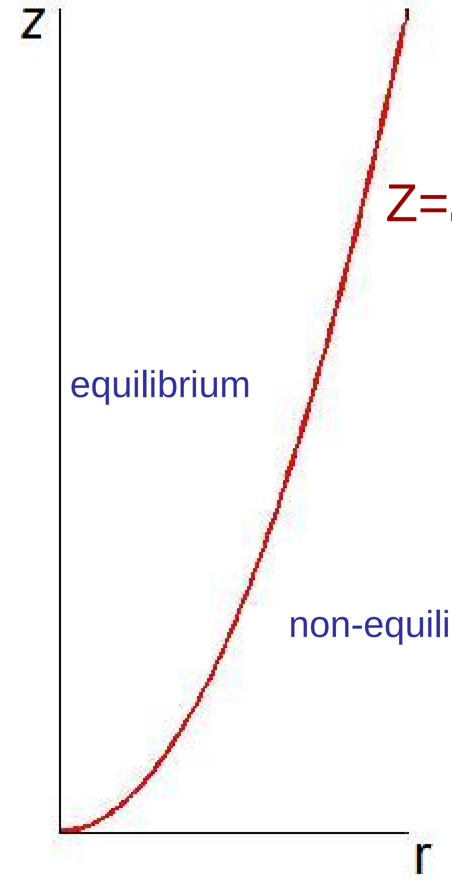
Collimation vs acceleration
2. Non-equilibrium jet

$$z < \frac{\Omega r^2}{c}$$

$$\Theta\gamma > 1$$



Poloidal field is negligible



Non-equilibrium jets are accelerated only up to $\gamma_t \sim \left(\frac{\gamma_{max}}{\Theta^2}\right)^{1/3}$

$$\sigma_t + 1 = \frac{\gamma_{max}}{\gamma_t} \sim \left(\gamma_{max}\Theta\right)^{2/3} > 1$$

Acceleration vs causality

Causality condition: $\phi > \Theta$

In the comoving frame
$$v'_{fms} = \frac{B'c}{\sqrt{4\pi\rho' + B'^2}} = c\sqrt{\frac{\sigma}{1+\sigma}}$$

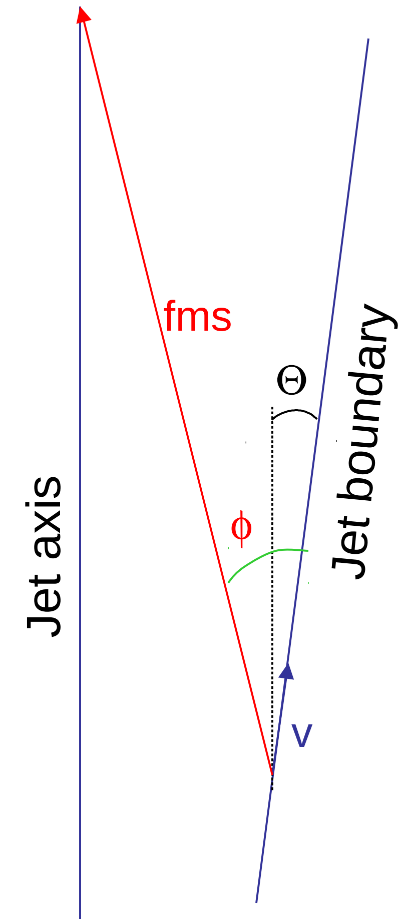
$$\gamma'_{fms} = \sqrt{1+\sigma}$$

In the lab frame
$$\phi = \frac{\gamma'_{fms}}{\gamma} = \frac{\sqrt{1+\sigma}}{\gamma}$$

Causality condition: $\gamma\Theta < \sqrt{1+\sigma}$

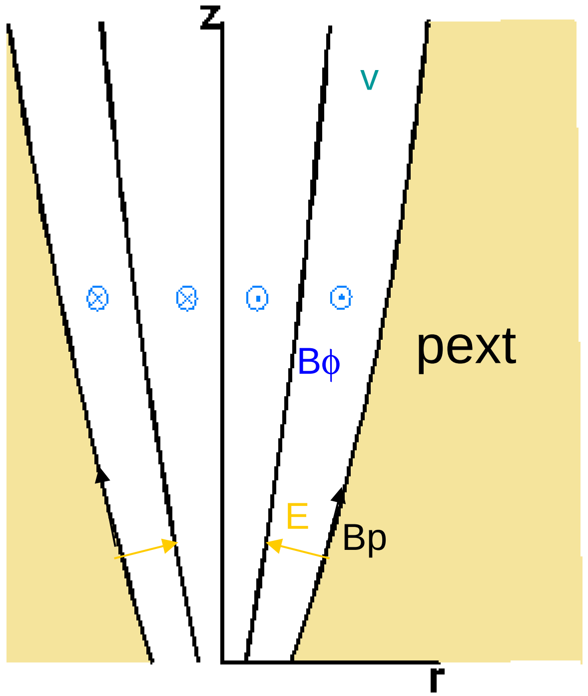
$$1+\sigma = \frac{\gamma_{max}}{\gamma} \quad \Rightarrow \quad \gamma < \left(\frac{\gamma_{max}}{\Theta^2}\right)^{1/3} = \gamma_t$$

Poynting dominated jets are accelerated
if they are causally connected



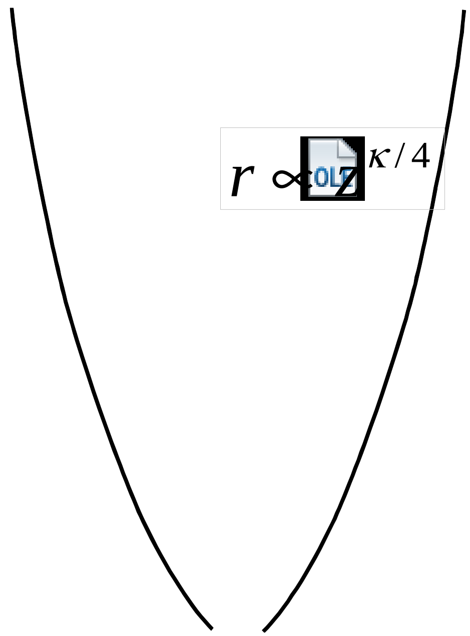
MHD jet confined by the external pressure

The spatial distribution of the confining pressure determines the shape of the flow boundary and the acceleration rate



MHD jet confined by the external pressure (cont)

$$p_{\text{ext}} = p_0 \left(\frac{R_L}{z} \right)^{\kappa}$$



1. Equilibrium jet; γ~*r/RL*

$$r \propto z^{\kappa/4} \qquad \gamma \propto z^{\kappa/4}$$

Equilibrium only if $r^2 < R_L z$

Equilibrium jet is formed if κ<2

The fastest acceleration at $\kappa \to 2; \quad \gamma \sim \Omega r / c \sim \sqrt{\Omega z / c}$

MHD jet confined by the external pressure (cont)

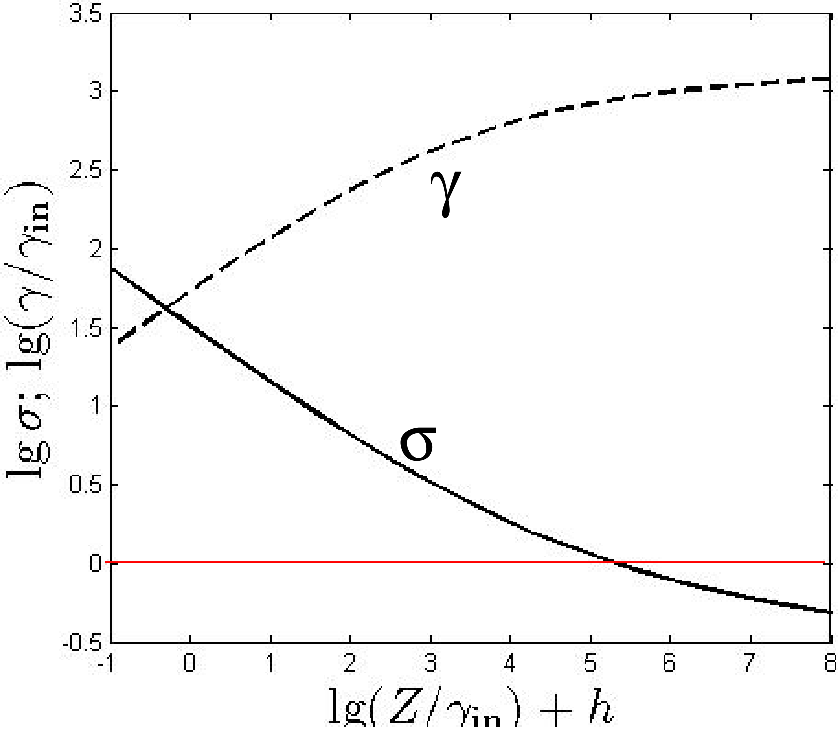
1. Equilibrium jet (cont)

Equipartition, σ~1; γ~γmax, at $z_0 \sim \gamma_{max}^{4/\kappa} R_L$

$$\text{At } \kappa \to 2,\ z_0 \sim \gamma_{max}^2 R_L$$

Beyond the equipartition:

$$\sigma \sim \frac{1}{\ln(z/z_0)}$$



MHD jet confined by the external pressure (cont)

$$p_{\text{ext}} = p_0 \left(\frac{c}{\Omega z} \right)^{\kappa}$$

2. Non-equilibrium jet; κ>2

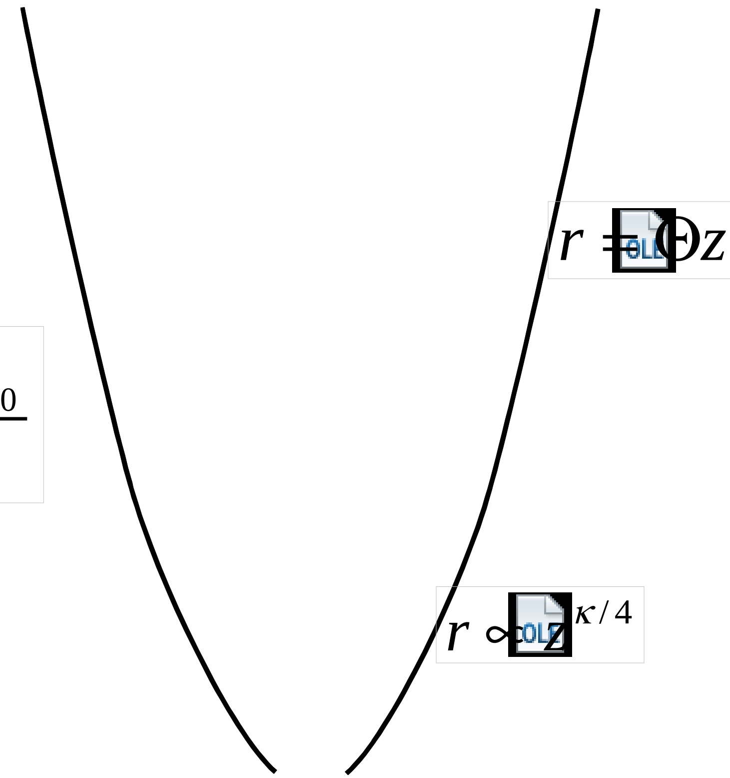
Jet asymptotically approaches conical shape $r = \Theta z$

$$\Theta = \frac{1}{\sqrt{\pi}} \Gamma\left(\frac{\kappa-1}{\kappa-2} \right) \left(\frac{(\kappa-2)^{\kappa}}{\beta} \right)^{1/[2(\kappa-2)]}; \quad \beta = \frac{8\pi p_0}{B_L^2}$$

$\Theta = 0.01/\beta^{2.5}$ at $\kappa = 2.2$

$\Theta = 0.2/\beta$ at $\kappa = 2.5$

$\Theta = 0.56/\sqrt{\beta}$ at $\kappa = 3$



MHD jet confined by the external pressure (cont)

2. Non-equilibrium jet; $\kappa>2$, (cont)

$$\gamma \text{ grows up to } \gamma_t \sim \left(\frac{\gamma_{max}}{\Theta^2}\right)^{1/3}; \quad 1+\sigma_t \sim \left(\gamma_{max}\Theta\right)^{2/3} > 1$$

In a layer that remains in causal contact with the external boundary of the jet, the flow is accelerated up to $\gamma \sim \gamma_{max}$, $\sigma \sim 1$.

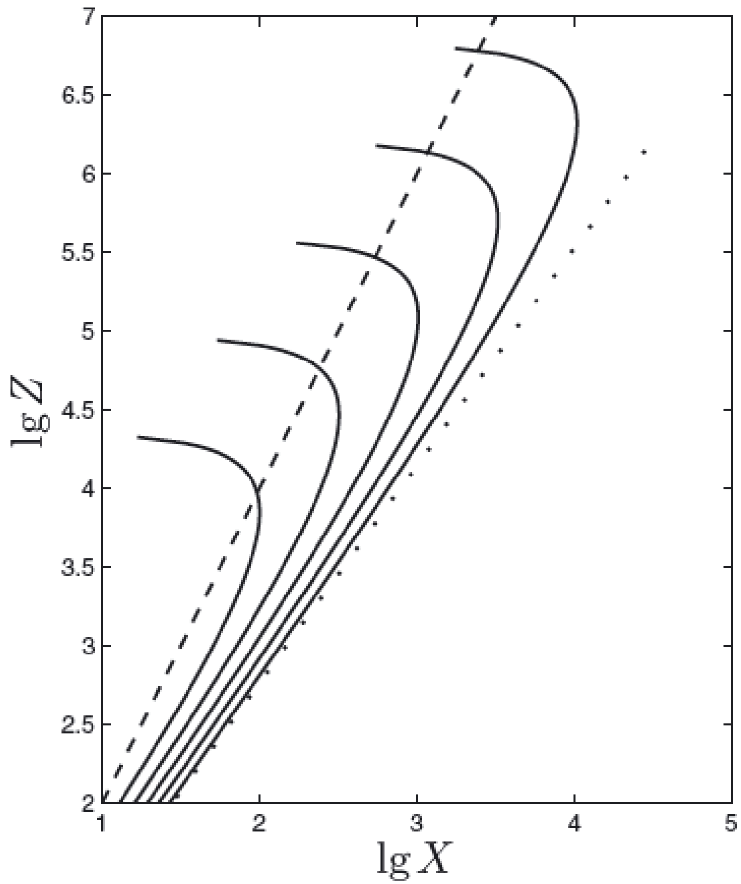
MHD jet confined by the external pressure (cont)

$$p_{\rm ext} = p_0 \left(\frac{c}{\Omega z} \right)^{\kappa} \qquad \beta \quad \frac{8\pi p_0}{B_L^2}$$

2. A special case; $\kappa=2$

At $\beta<1/4$, the flow is parabolic and goes to infinity

At $\beta<1/4$, the flow is accelerated till $\sigma\sim1$ and then collapses.



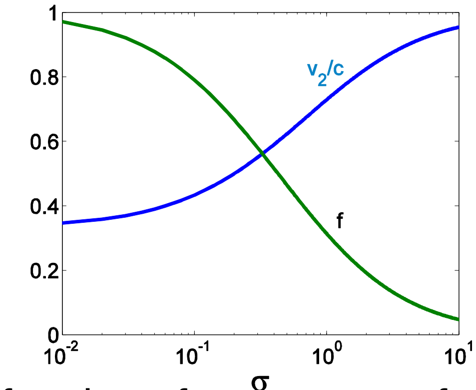
Dissipationless MHD jets; summary

1. Externally confined Poynting dominated outflows are efficiently collimated and accelerated to high Lorentz factors.

2. The acceleration zone spans a large range of scales .

3. Acceleration up to equipartition between the magnetic and kinetic energy ($\sigma \sim 1$) is possible in causally connected flows ($\Theta\gamma \leq$ few). Transition to the matter dominated stage, $\sigma \sim 0.1$, could occur only at an unreasonably large scale.

The kinetic energy is released at shocks. But most of the flow energy could be released at a shock only if $\sigma < 0.1-0.2$. Only such a flow could be considered as matter dominated

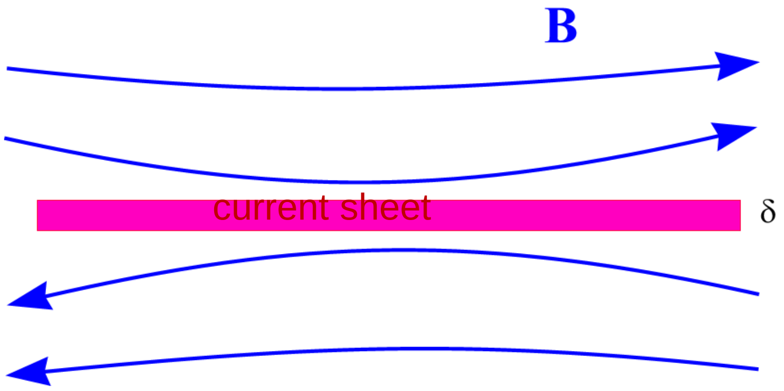


f- fraction of energy transferred to the plasma at a relativistic shock.
Compression ratio = c/v2

4. These conditions are rather restrictive. It seems that in real systems, some sort of dissipation is necessary in order to utilize the electromagnetic energy completely.

Beyond the ideal MHD:
magnetic dissipation in Poynting dominated outflows

The magnetic energy could be extracted via anomalous dissipation that comes into play if the magnetic field varies at micoscopic scale (e.g., in narrow current sheets).

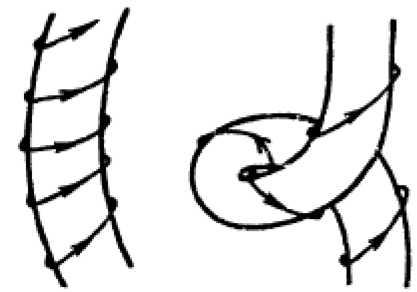


How differently oriented magnetic field lines could come close to each other?

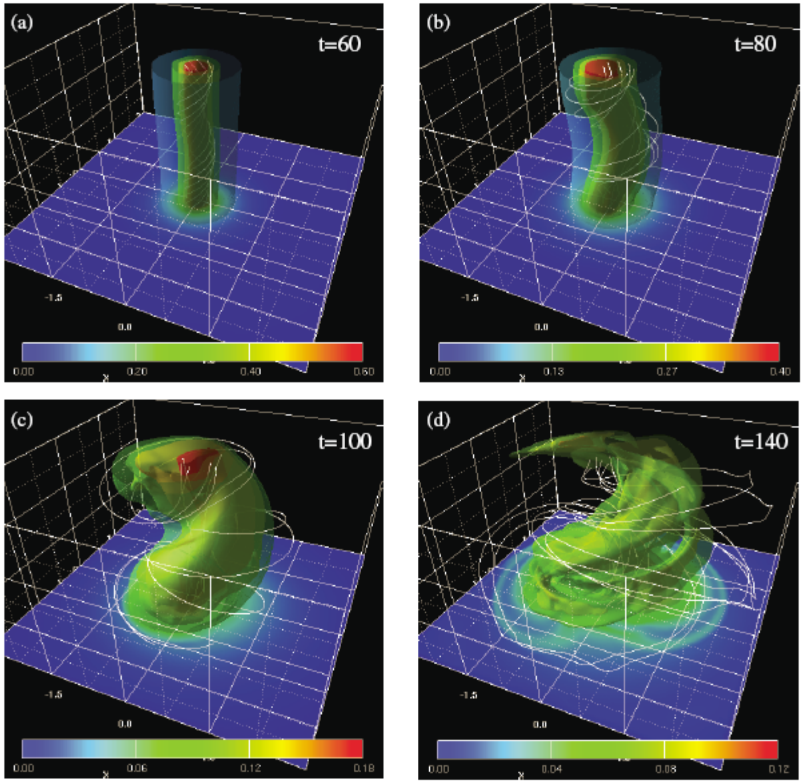
1. Global MHD instabilities could disrupt the regular structure of the magnetic field thus liberating the magnetic energy.
2. Alternating magnetic field could be present in the flow from the very beginning (striped wind).

Global MHD instabilities

The most dangerous is the kink instability.



In expanding jets, the necessary condition for the instability – strong causal connection, $\gamma\Theta<1$. Not fulfilled in GRBs; fulfilled in AGNs.



Simulations of the kink instability; time is in units *rj/c* (Mizuno et al 2012)

Kink instability in relativistic jets

The instability growth rate in the comoving frame : $\kappa = \zeta \frac{c}{r_j}$
For a static column, $\zeta \sim 0.1$.

When $\frac{dB_z}{dr} \to 0$, which is possible only in relativistic, not rigidly moving jets, $\zeta \to 0$ (Istomin & Pariev '96; L '99)

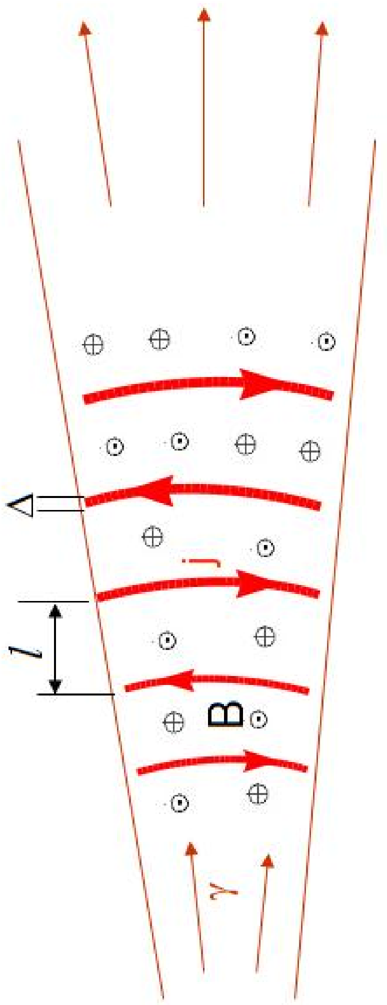
Cylindrical equilibrium:

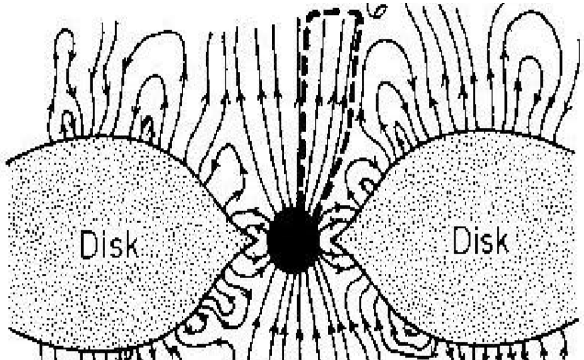
$$\frac{E}{r}\frac{d}{dr}rE = B_z\frac{dB_z}{dr} + \frac{B_\varphi}{r}\frac{drB_\varphi}{dr}$$

$$E = \frac{\Omega r}{c}B_z$$

Simulations of jet launching by a spinning accreting black hole reveal that in real Poynting-dominated jets, the poloidal field is very close to uniform (Tchekhovskoy et al. '08). The kink instability is saturated in this case (Mizuno et al '12).

But when the jet is accelerated up to $\sigma \sim 1$, the poloidal flux is concentrated toward the axis (Beskin Nokhrina '09; L '09); such a configuration is subject to disruptive kink instability (Mizuno et al '12). A possible scenario for the magnetic energy release in strongly causally connected jets (AGNs): they are smoothly accelerated up to $\sigma \sim 1$ and then the regular structure is disrupted by the kink instability.





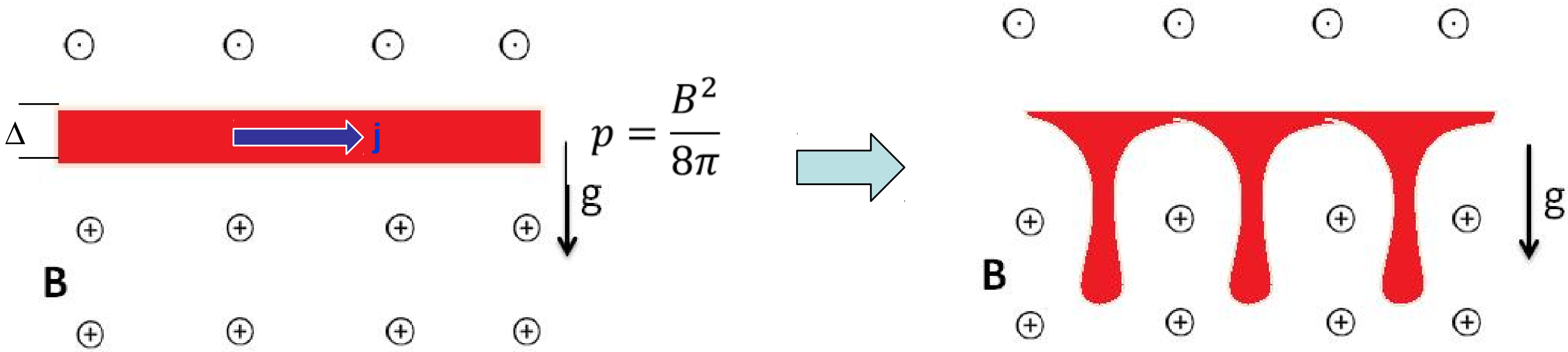
Could alternating magnetic field be presented in the flow from the very beginning?

Let alternating fields preexist in the jet

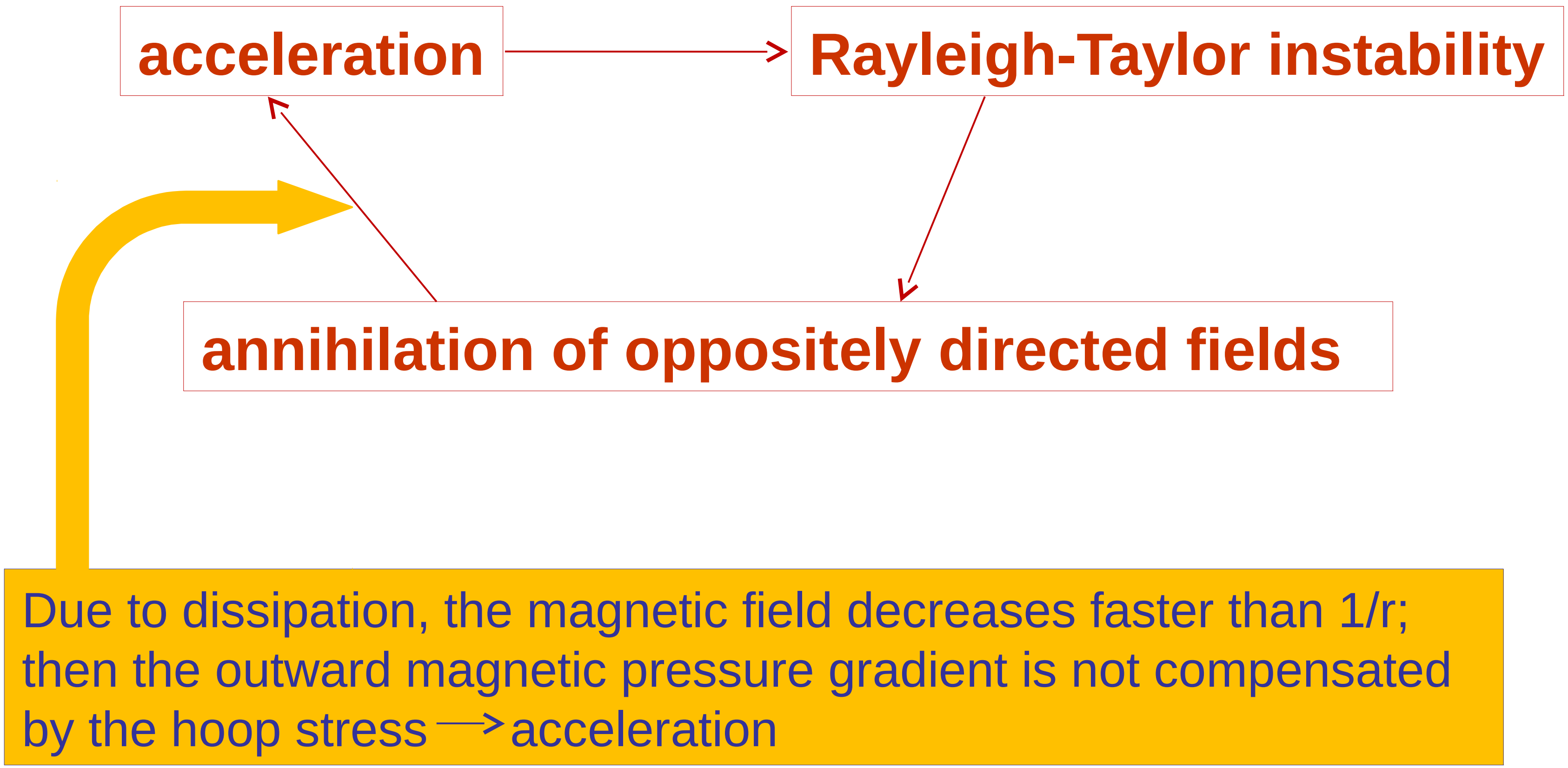
In an expanding flow, B becomes predominantly toroidal; current sheets are stretched. Local structure: plane current sheet separating oppositely directed fields. What is the magnetic dissipation mechanism in this *case?*

Rayleigh-Taylor instability of current sheets in accelerating flows (L ‘10)

In an accelerating relativistic flow $g = c^2 \frac{d\gamma}{dr}$



Time scale $\tau = \xi \sqrt{\frac{\Delta}{g}}$


acceleration
Rayleigh-Taylor instability
annihilation of oppositely directed fields
Due to dissipation, the magnetic field decreases faster than 1/r;
then the outward magnetic pressure gradient is not compensated
by the hoop stress → acceleration

Interplay between acceleration and dissipation; a self-consistent picture

$$\gamma = \left(\frac{9\gamma_{max} z}{4\xi^2 l}\right)^{1/3} \qquad \frac{\Delta}{l} = \left(\frac{z}{12\gamma^2{}_{max}\xi^2 l}\right)^{1/3}$$

Complete dissipation: $\Delta \sim l$; $\gamma \sim \gamma_{max}$; $z_{diss} \sim (\xi\gamma_{max})^2 l$

In accreting systems: $l \sim R_g$

$$z_{diss} \sim \begin{cases} 10^3 \left(\frac{\xi\gamma}{30}\right)^2 R_g & \text{AGNs} \\ 10^7 \left(\frac{\xi\gamma}{1000}\right)^2 R_g & \text{GRBs} \end{cases}$$

Conclusions

1. External confinement is crucial for efficient collimation and acceleration of Poynting dominated outflows.

2. Efficient acceleration is possible only in causally connected flows.

3. In Ponting dominated jets, the conventional two-step model

   Poynting → kinetic → radiating particles

   faces difficulties in both steps. A one-step process

   Poynting → radiating particles

   looks promising. This implies either global MHD instability (kink) or alternating fields preexisted in the flow.

4. The magnetic energy could be released due to the kink instability in strongly causally connected flows ($\gamma\Theta<1$, fulfilled in AGNs) after the equipartition ($\sigma\sim1$) is achieved.

5. If alternating field preexisted in the flow, they are efficiently dissipated via the Rayleigh-Taylor instability. The necessary effective gravity is self-consistently maintained because magnetic dissipation results in the acceleration of the flow.