Waves and energy dissipation in magnetically dominated flows

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σ-problem

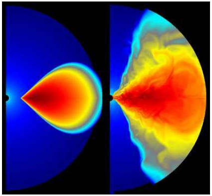
- outflows from rotating compact objects are powered hydromagnetically
- wind energy carried by Poynting flux
- the flow is highly magnetized but emission sites weakly magnetized

  blazar jets $\sim$ equipartition Readhead+ '94, Ghisellini+ '14

  pulsars $\sigma \sim 10^{-3}$ Kennel & Coroniti '84
- what is the dissipation mechanism?
- gradual acceleration, confinement by ext. medium? dependent on boundary conditions Lyubarsky '09, '10
- shocks in high sigma plasmas are not effective Kennel & Coroniti '84

Beyond MHD – low density flows

- dense plasma – MHD framework
- but density can be small in the jet funnel; in a radial flow it drops with distance $n \propto r^{-2}$
- at some point MHD not a good approximation
- not screened $E_{||}$ (gaps)? relativistic drift-speed and nonlinear waves? Usov '75, Melatos & Melrose '96, ...
  - they can describe non-MHD regime of freely expanding, initially MHD flows; shock can trigger dissipation by EM precursors
  - description by two fluid eqs (cold $e^{\pm}$) + Maxwell eqs



McKinney & Gammie '04,...

Nonlinear plane waves

- search for plane wave solutions Max & Perkins, Clemmow, Kennel & Pellat, Asseo+...
- wave described by its phase velocity β, fluids: momenta $\boldsymbol{p}_{||} = \boldsymbol{p}_{||,+} = \boldsymbol{p}_{||,-} \,||\, \boldsymbol{\beta}$ and $\boldsymbol{p}_{\perp} = \boldsymbol{p}_{\perp,+} = -\boldsymbol{p}_{\perp,-}$
- to solve eqs introduce the phase variable

$$\phi = \omega \left(t - \frac{x}{c\beta} \right)$$

- transform coordinates to the frame moving with 4-vel. $\boldsymbol{U} \,||\, \boldsymbol{\beta}$

$$\phi = \omega \left[t' \left(\Gamma - \frac{U}{\beta} \right) + \frac{x'}{c} \left(U - \frac{\Gamma}{\beta} \right) \right]$$

- two convenient frames: 1) $U = \Gamma\beta$, 2) $U = \Gamma/\beta$
- they define different modes: MHD-like $\beta < 1$; EM $\beta > 1$

Nonlinear plane waves (circular polarisation)

	magnetic shear	EM mode
phase velocity	$\beta < 1$	$\beta > 1$
group velocity	$\beta_{\mathrm{w}} = \beta$	$\beta_* = 1/\beta < 1$
comoving frame	$E = 0$	$E \neq 0$
	$p_\perp \vert\vert B$	$p_\perp \perp E$
	only spatial dep.	only time dep.
particle accel.	no	yes

- radial propagation and thus spherical effects on the wave amplitude and particle motion treated as a perturbation $\epsilon = \lambda/r = c/\omega r \ll 1$ Asseo+ '84, Mochol & Kirk '13a

  very different behaviour for two different modes

Radial evolution – magnetic shear

three phases

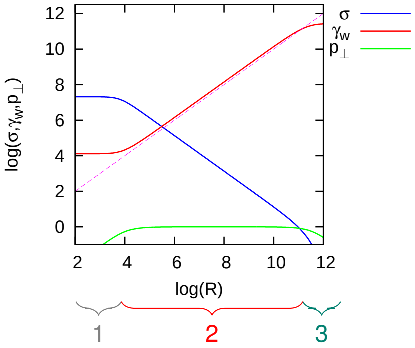
$$R = r\omega/(4\kappa c)$$

1. coasting, super-FMS
$R \ll R_{\rm acc}$
$p_\perp \ll 1,\ \gamma_{\rm w} \approx {\rm const},\ \sigma \approx {\rm const}$

2. acceleration
$R_{\rm acc} \ll R \ll R_{\rm diss}$
$p_\perp \approx 1,\ \gamma_{\rm w} \propto R,\ \sigma \propto R^{-1}$

3. $R \gg R_{\rm diss}$
$p_\perp \ll 1,\ \gamma_{\rm w} \approx {\rm const},\ \sigma \ll {\rm const}$

$$R_{\rm acc} = a_0/4\kappa\sigma_0, \quad R_{\rm diss} = a_0/(4\kappa)$$



Kirk & Mochol '10

Radial evolution – EM mode

launch by a mode conversion from an MHD wave; initial conditions from "EM jump conditions" Kirk '10, Arka & Kirk '12

- mode conversion triggered by ext. cond. $\rightarrow$ precursors of shocks in low-density plasma
- propagation if $\omega > \omega_{\mathrm{p}}/\sqrt{\gamma_{\mathrm{max}}}$
- $\beta_*(r) \propto 1/r^2$
  $p_{||}(r) \propto \gamma_*^2/r^2$
  $p_\perp(r)$ increases
  $\langle\gamma\rangle(r) = \mathrm{const}$
- when propagation possible waves generated as shock precursors Amano & Kirk '13
- initial properties depend on where the wave is launched: close to the critical point the amplitude is the largest Mochol & Kirk '13a

Radiative signatures

- magnetic shear: only IC possible

- EM mode: synchro-Compton + IC
- in eccentric pulsar binaries EM precursors appear at shock only when stars separated enough
- when EM precursors appear at certain orbital phase, strong emission expected Mochol & Kirk '13b, '14: Fermi-flare in B1259-63

Summary

- nonlinear waves important to describe outflows in the low-density regime:

  freely-expanding jets when charge-starvation

  in confined flows as superluminal shock precursors