Dissipation and generation of magnetic field in relativistic flows

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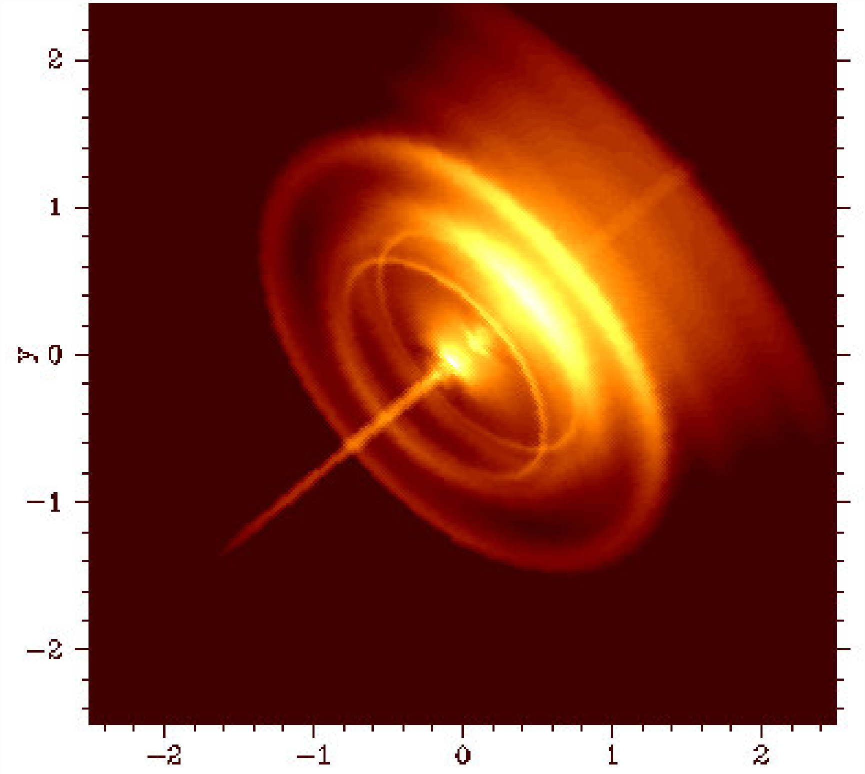
Pulsar winds



2D relativistic MHD
by at least three groups

Komissarov & Lyubarsky 2003;

Khangoulian & Bogovalov 2003;

Del Zanna et al 2004

Key ingredients:

- relativistic, anisotropic wind (power$\propto \sin^2\theta$)
- low magnetisation σ (at least near equator)

Implications for the wind

Exact solution for force-free, split monopole (Michel 1973): no collimation, $B_\phi \propto \sin\theta/r$ (no closed field lines)

Super-(magneto)sonic flow: $\Gamma \rightarrow$ constant (Bogovalov 1997)

$$\begin{aligned} \sigma &= \frac{B^2/8\pi}{\Gamma n m c^2} \\ &= \text{constant} \end{aligned}$$

cannot match inner and outer boundary conditions

Possible solutions to the σ problem

Accelerate the wind:

- Collimation? Not for monopole-like flows (e.g., Bogovalov & Tsinganos 1999) but in principle possible (Vlahakis 2004)
- Dissipation? Oblique rotator (Coroniti 1990) and damping of wave component — how fast?

Problem not really a problem:

- σ still high after the shock (Begelman 1998)? Difficult to recover nice pictures. . .
- the (striped) field dissipates in the termination shock (Lyubarsky 2003) Transition must remain thin

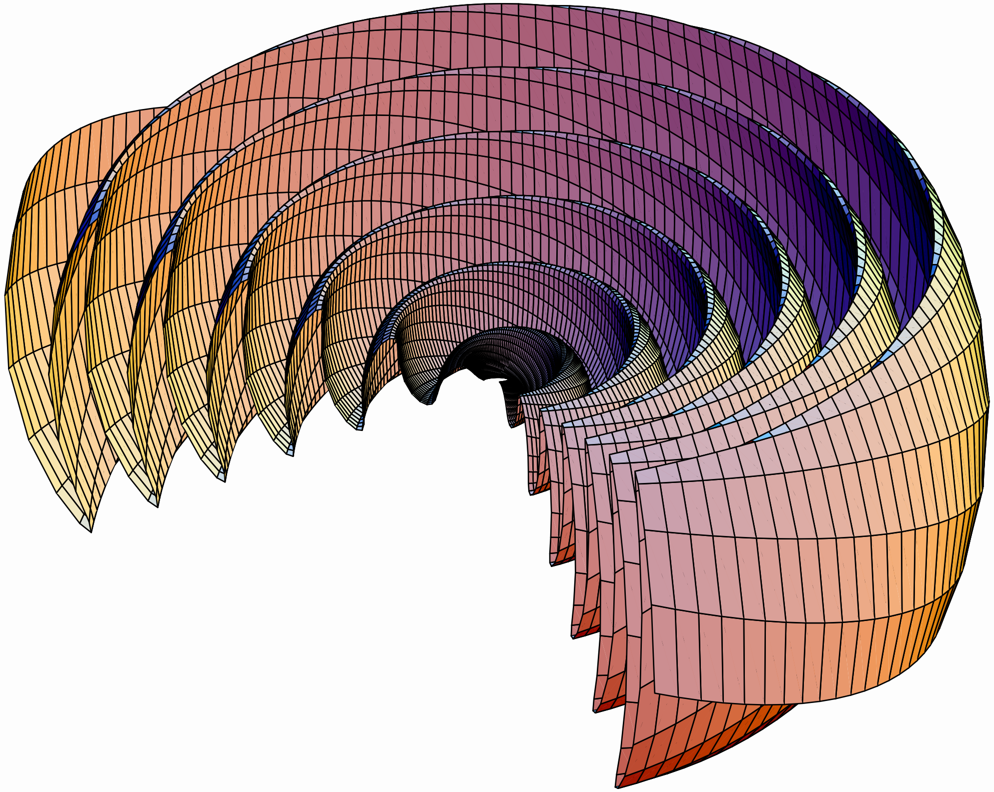
Acceleration of the wind

Dissipation forced by charge starvation ($B \propto 1/r$, $n \propto 1/r^2$)

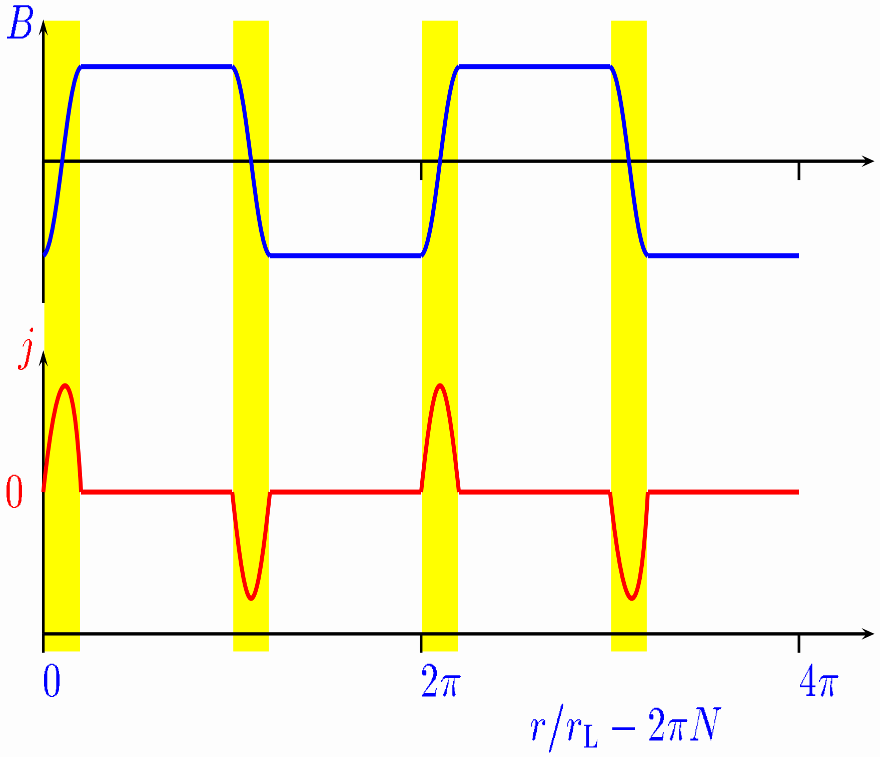
Entropy wave or FMS wave

Lyubarsky & Kirk 2001;

Lyubarsky 2003;



Current sheets



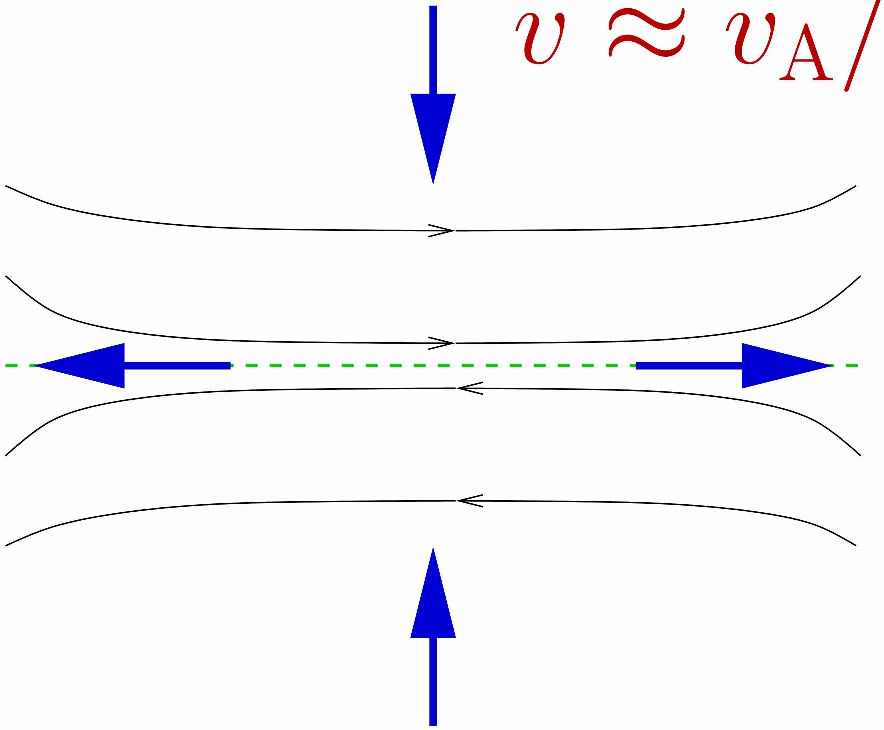
Magnetic pressure balanced by hot plasma in sheet.

Key question:

What controls the dissipation rate?

Relativistic vs nonrelativistic reconnection

Nonrelativistic, 2D picture



$$v \approx v_{\mathrm{A}}/R^{1/2}$$

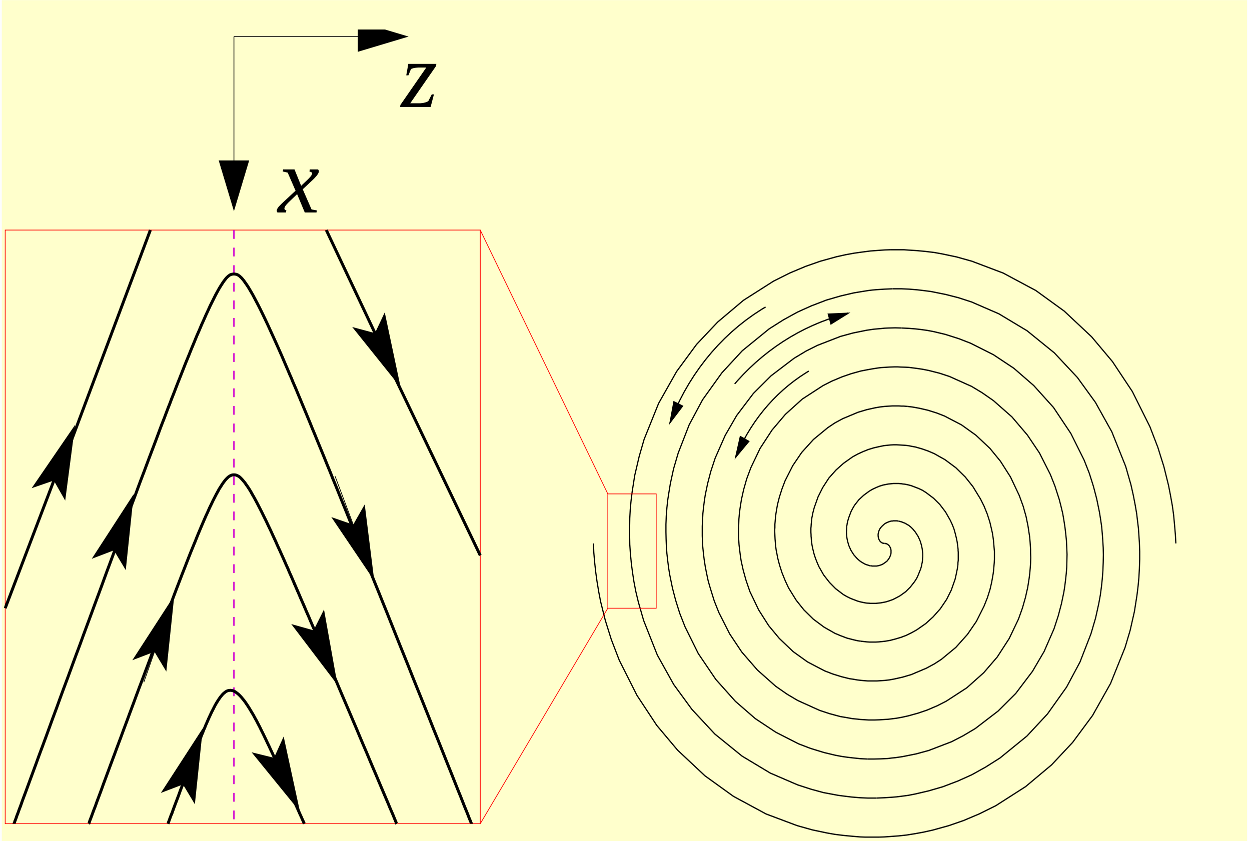
$$v \approx v_{\mathrm{A}}$$

Plasma ejected at approximately Alfvén speed.

$R =$ ratio macro/micro lengthscales

Relativistic vs nonrelativistic reconnection

Relativistic current sheets



PRL (2004)

Stationarity $\Rightarrow$ superluminal “drift” speed

B_z cannot eject particles $\Rightarrow$ finite length in y direction

Pulsar wind vs accretion driven jet

Similarities:

Differences:

Pulsar wind vs accretion driven jet

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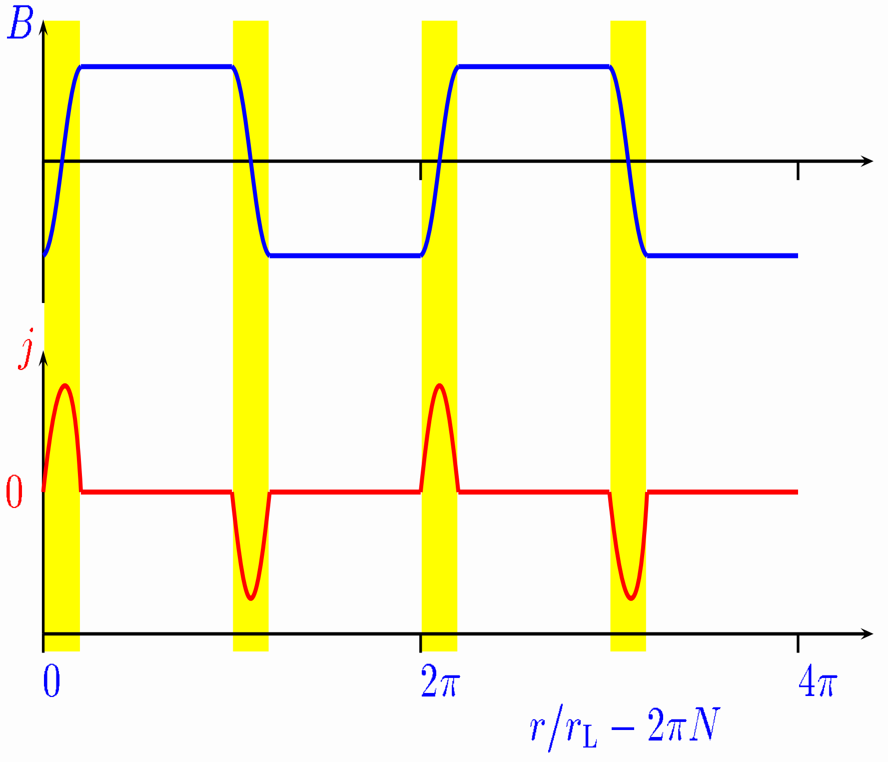
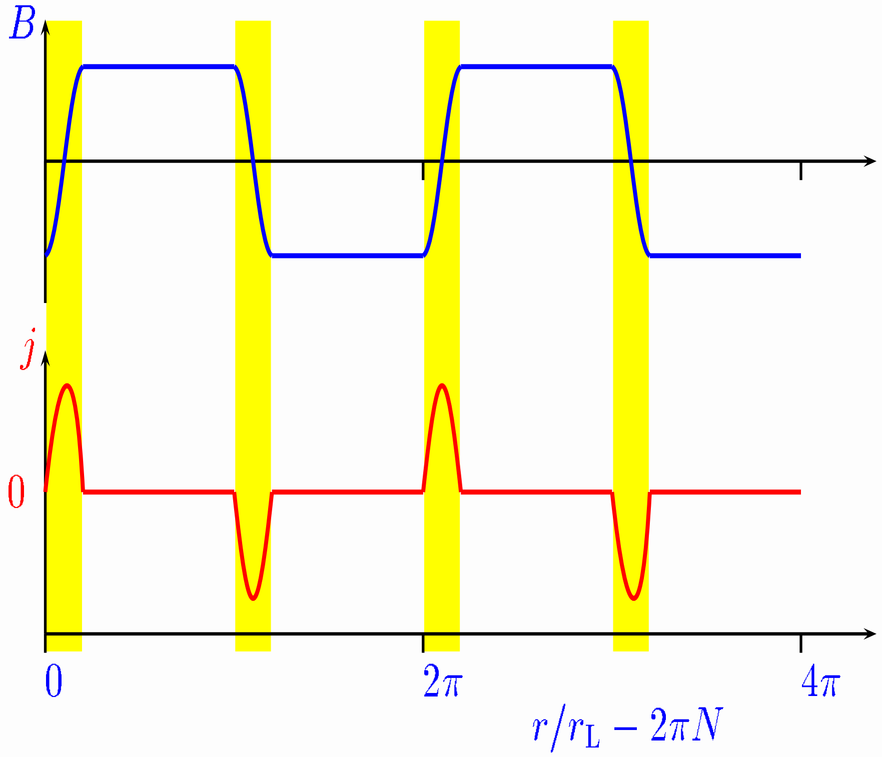
- Complications due to photosphere
- Modest Lorentz factors
- No periodicity

Current sheets



Microphysics issues:

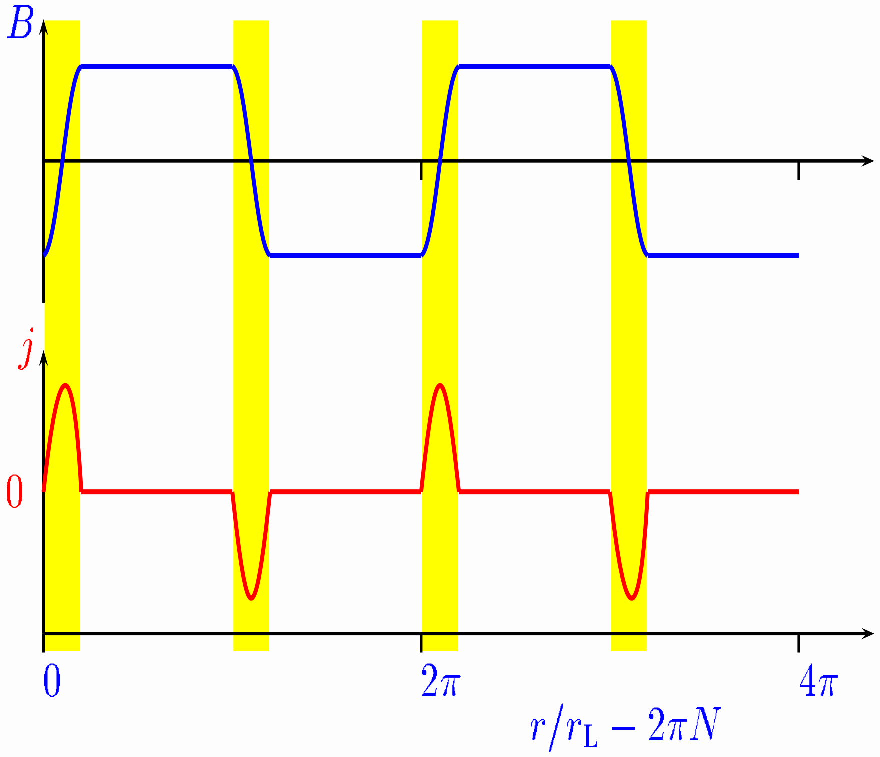
Current sheets



Microphysics issues:

Slow vs Rapid growth?
Radiative signature

Current sheets



Microphysics issues:

Slow vs Rapid growth?
Radiative signature

Two-phase medium?
Ratio Synch/IC

Modelling the dissipation

Short wavelength approximation (Kirk & Skjæraasen 2003)

Slow dissipation	*Tearing-mode*	*Fast*
Coroniti (1980); Michel (1994); Lyubarsky & Kirk (2001)	Lyubarsky (1996)	Drenkhahn & Spruit (2002)
$\Gamma \propto r^{1/2}$	$\Gamma \propto r^{5/12}$	$\Gamma \propto r^{1/3}$
$\frac{r_{\mathrm{max}}}{r_{\mathrm{L}}} = \hat{L}^{1/2}$	$\frac{r_{\mathrm{max}}}{r_{\mathrm{L}}} = \mu^{4/5}\hat{L}^{3/10}$	$\frac{r_{\mathrm{max}}}{r_{\mathrm{L}}} = \mu^{4/5}\hat{L}^{3/10}$

$\hat{L} = L(\pi^2 e^2/m^2 c^5)$, ($= 1.5 \times 10^{22}$ for Crab)

No consistent conversion mechanism for $\mu > 10\hat{L}^{1/4}$

Amplification of B

“Needed” at shocks in several scenarios:

- GRB
- Radio supernovae
- Supernova remnant shocks

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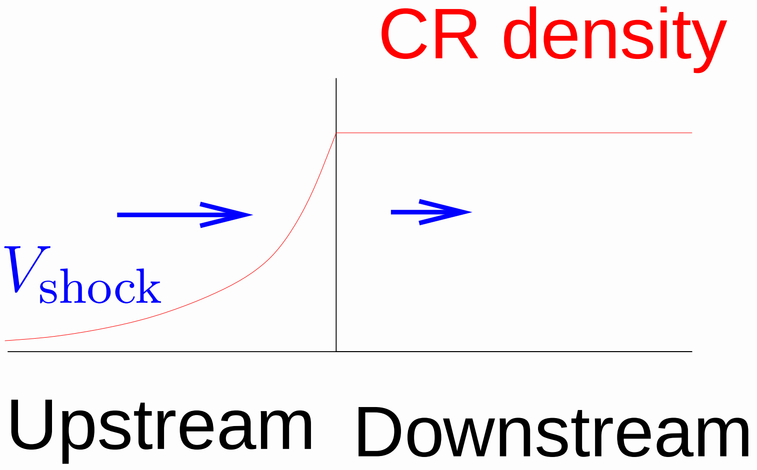
High Mach number/relativistic shock formation problem

Leave it to the PIC artists?

SNR shocks

- Diffusive shock acceleration: CR density constant downstream, falls off exponentially upstream
- In plasma frame, CR streaming speed $\approx$ shock speed
- Standard linear analysis for three component plasma: background protons and electrons, plus CR's, parallel shock, parallel propagation (Achterberg 1981)



SNR shocks

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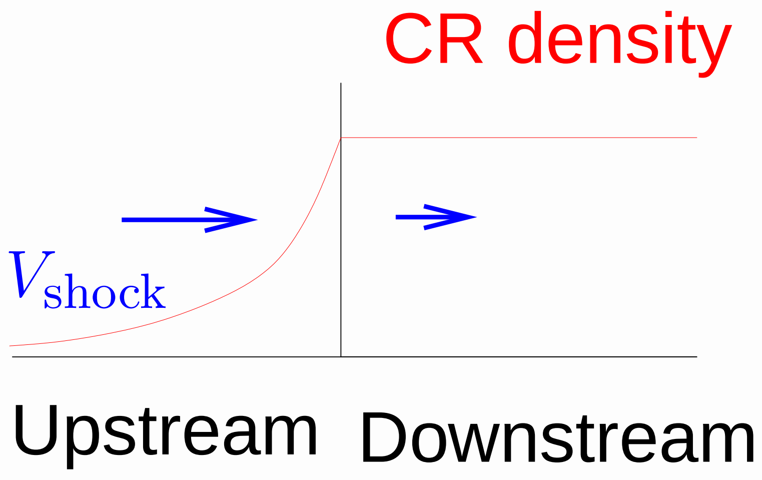


Modification of low freq. wave modes unimportant → Alfven waves grow at the CR cyclotron resonance

Bell’s (2004) instability

- But, shorter wavelength modes with

$$r_{\rm thermal}^{-1} \quad > \quad k \; > \; r_{\rm CR}^{-1}$$

strongly modified.

- Plasma uncompensated: helicon/whistler-type modes
- Strong, nonresonant growth driven by “uncompensated” current.

Nonlinear development

Saturation expected when

$$\begin{aligned} \left|\vec{k} \wedge \vec{B}\right| &\approx \frac{4\pi}{c} j_{\mathrm{CR}} \\ \Rightarrow \frac{B^2}{8\pi} &\approx \frac{1}{2}\frac{v_{\mathrm{CR}}}{c} U_{\mathrm{CR}} \end{aligned}$$

SNR shock: $v_{\mathrm{s}}/c = 1/50$, $M_{\mathrm{A}} = 200$, $\beta \approx 1$:

$$\begin{aligned} U_{\mathrm{CR}} &\approx M_{\mathrm{A}}^2 B_{\mathrm{ISM}}^2/8\pi \\ \Rightarrow B_{\mathrm{shock}} &\approx 30 B_{\mathrm{ISM}} \end{aligned}$$

Acceleration to $> 10^{15}$ eV?

Relativistic case

- Relativistic proton beam $\Gamma_{\rm b} \gg 1$
- Warm electron/proton plasma $kT/m = \Theta$
- Charge neutrality, zero net current

$$\Rightarrow \omega^2\chi \approx -\underbrace{\frac{\omega'_{\rm pb}{}^2\omega'}{\epsilon\omega_{\rm c}}}_{\text{plasma current}} + \underbrace{\frac{\omega'_{\rm pb}{}^2\omega'}{\epsilon\omega_{\rm c}-\omega'}}_{\text{beam response}} + \frac{\omega^2}{v_{\rm A}^2} + \underbrace{\frac{\omega_{\rm p}^2\omega'}{\epsilon\omega_{\rm c}^3}\left(k^2-\omega^2\right)\left\langle\gamma^2 v_\perp^2\right\rangle}_{\text{thermal effects}}$$

Relativistic case

Cold plasma, $\epsilon = -1$: purely growing modes, max. growth rate

$$\mathrm{Im}\left(\hat{\omega}\right) \approx \frac{n_\mathrm{b}}{n_\mathrm{p}}\omega_\mathrm{p} \qquad \text{at} \qquad \hat{k} \approx \frac{\Gamma n_\mathrm{b}}{v_\mathrm{A}^2 n_\mathrm{p}}$$

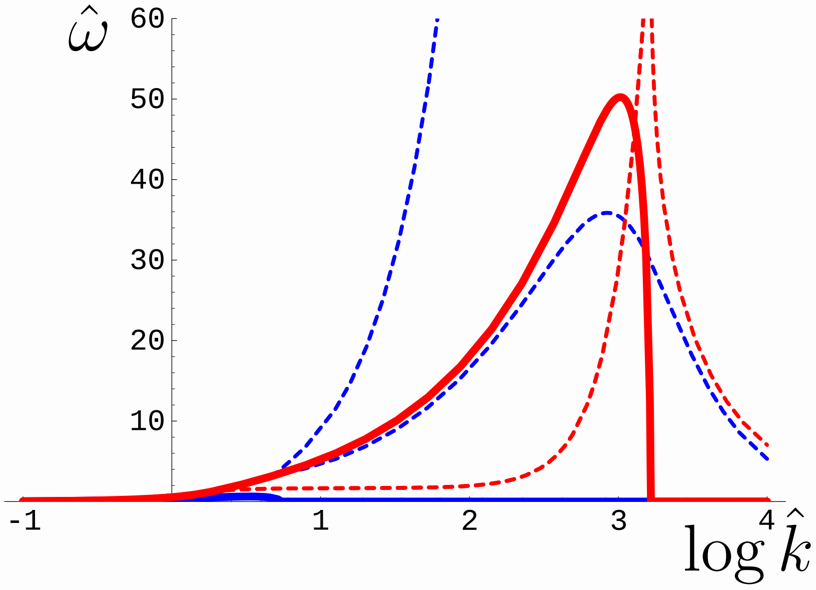
Thermal effects reduce current drive when

$$\hat{k} > \left(\frac{\Gamma n_\mathrm{b}}{n_\mathrm{p}\left\langle\gamma^2 v_\perp^2\right\rangle}\right)^{1/2}$$

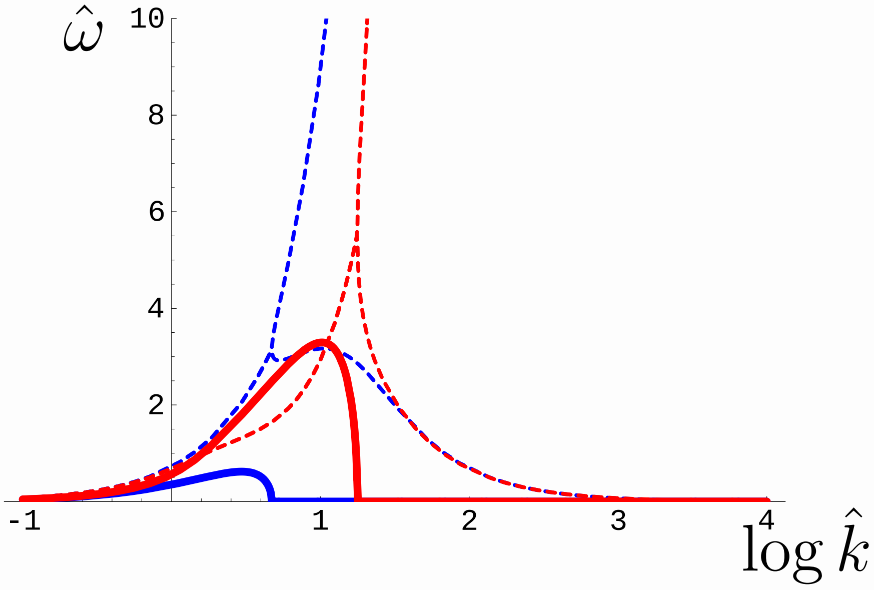
i.e.,
$$\Theta > v_\mathrm{A}^2\sqrt{\frac{n_\mathrm{p}}{\Gamma n_\mathrm{b}}}$$

Relativistic case

e.g., $v_{\mathrm{A}} = 2 \times 10^{-5}$, $\Gamma = 10$, $n_{\mathrm{b}}/n_{\mathrm{p}} = 1/3$, $\epsilon = -1$, $\epsilon = +1$



$\Theta = 1/1000$



$\Theta = 1/10$

Summary

- Bell’s mechanism promising for magnetic field amplification in SNR shocks
- Same physics operates in relativistic shock scenario
- Field amplification limited by thermal effects