Particle acceleration in magnetically dominated jets

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Outline

- Introduction — how to dissipate EM fields
- Under-dense plasmas in jets?
- Two-fluid and Monte-Carlo simulations of particle acceleration

Problem

- Relativistic jets are thought to be launched with high magnetization parameter: $\sigma \gg 1$.
- Collimation slow $\Rightarrow \sigma$ may remain $\gtrsim 1$, even at pc scale.

  Lyubarsky MN 2010
- Fermi I acceleration doesn't work well in shocks with $\sigma \gtrsim 10^{-3}$ (low compression, particles advected away).
- Reconnection needs a current sheet and a trigger.

Potential Solution

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- Wait long enough JK & Mochol (2011)
- Hit an obstacle:
  - MHD: compress current sheets $\Rightarrow$ at a weak shock $\Rightarrow$ enhance reconnection rate. Solar wind: Drake et al (2010) Pulsars: Cerutti et al (2014) Blazars: Sironi, Giannios & Petropoulou (2015)
  - *Under-dense* plasma: fluctuations reflected as electromagnetic modes forming a dissipative precursor

    Amano & Kirk (2013), Mochol & Kirk (2013)

Under-dense zones in a conical $e^{\pm}$ jet/beam

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Constraints/Estimates:

1. $a_0 = 3.4 \times 10^{14} \sqrt{4\pi L_{46}/\Omega_\mathrm{s}}$
2. $\sigma_0 \lesssim \mu^{2/3}$ (for a supermagnetosonic jet)
3. Pair multiplicity $\kappa_0 = a_0/(4\mu) > 1$

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Fluctuation wavelength $2\pi\lambda\!\!\!^{-}$ $a_0 \gg \mu \gg \sigma \gg 1$

Over-dense | Under-dense

$r = \lambda\!\!\!^{-} a_0/\mu$

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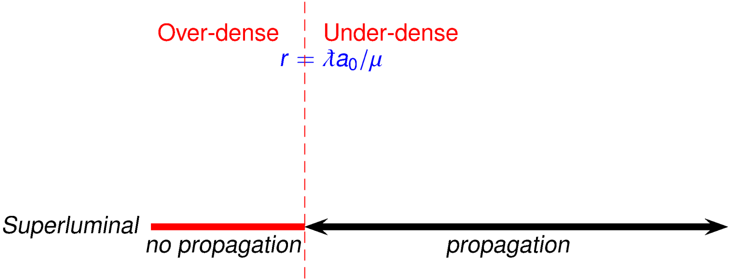

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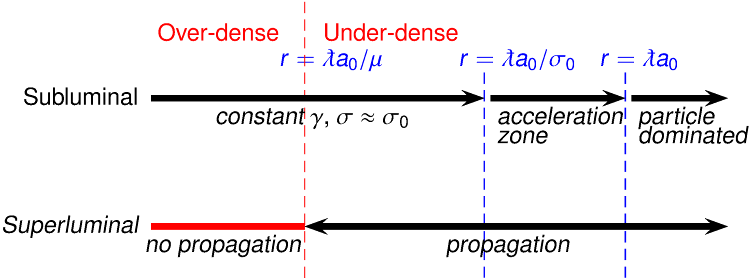

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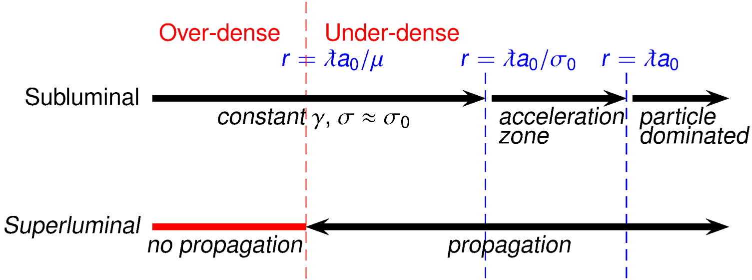


$\kappa_0 = 1$	$4 \times 10^{15}\mathrm{cm}$	$10^{20}\mathrm{cm}$
$\kappa_0 = 10^3$	$4 \times 10^{18}\mathrm{cm}$	$10^{22}\mathrm{cm}$

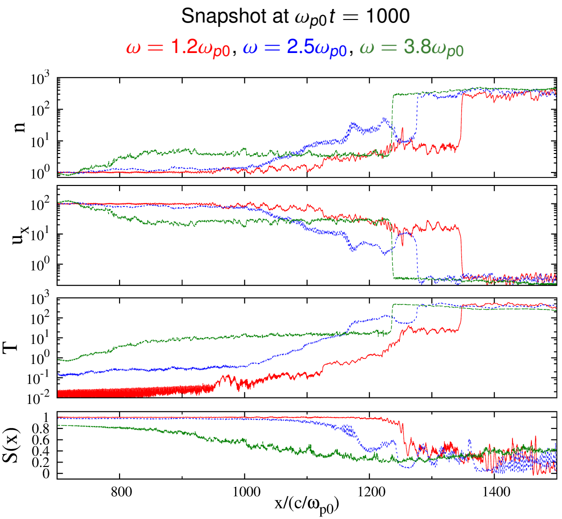
(Estimates for M87: $L = 10^{41}\mathrm{erg/s}$, $\Omega_s/4\pi = 0.0006$, $\lambda\!\!\!^{-} = r_g = 10^{15}\mathrm{cm}$)

Two-fluid simulations

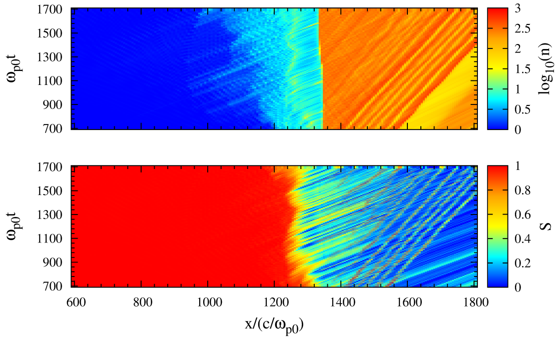
Beyond MHD: simplest description that includes superluminal, electromagnetic modes is two-fluid $e^{\pm}$ Amano & Kirk ApJ (2013) Initial conditions:

- Left half: circularly polarized, cold, static shear
- Supersonic: $\Gamma > \sigma^{1/2}$
- Under dense: $\lambda \lesssim c/\omega_{\mathrm{p}}$
- Search for quasi-stationary precursor

Precursor for $\Gamma_u = 100$, $\sigma = 25$



Steady state for $\Gamma_u = 100$, $\sigma = 25$, $\omega = 1.2\,\omega_{p0}$



$$S = \frac{\sigma(x)}{\sigma}$$

$\omega_{p0} t$ [0 : 1700], $x/(c/\omega_{p0})$ [0 : 2000]

$x_{sh}/(c/\omega_{p0}) = 1335$, $x_{precursor}/(c/\omega_{p0}) = 1175$

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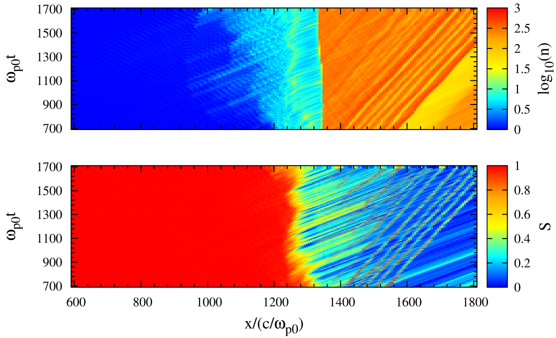

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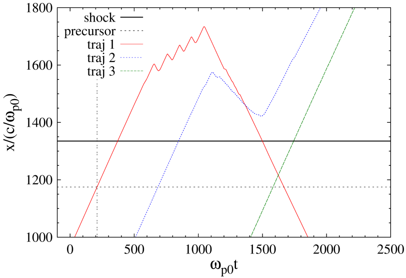
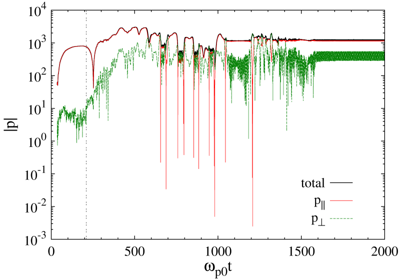
Stationary precursor for $\omega \gtrsim \omega_{p0} \iff r \gtrsim \lambda a_0/\mu$

Test-particle trajectories

Particles followed until they reach upstream or downstream boundary

trajectory n. 1





Electrons energised in the precursor and reflected downstream of the shock.
Acceleration in the direction perpendicular to the bulk motion.

Monte-Carlo simulations of Fermi-I acceleration

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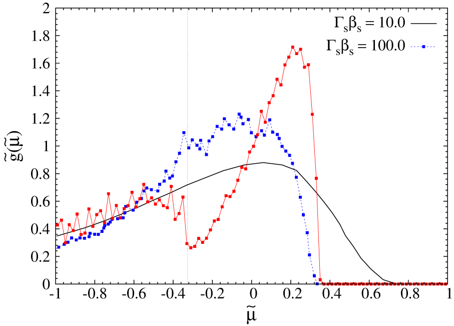
Compare with s=4.23 for unmagnetised relativistic shock and s=4.28 for relativistic shocks with uniform upstream field.

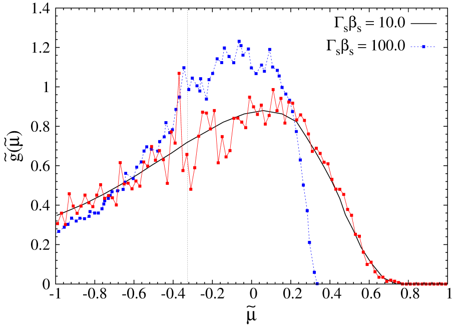
Deflection upstream, regime I

$$L_{scat,u} \gg \lambda_u \gg r_{g,u} \implies s = 4.29 \pm 0.01$$



Deflection upstream, regime II

$$r_{g,u} \gg L_{scat,u} \gg \lambda_u \implies s = 4.23 \pm 0.01$$



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- Particles injected into a Fermi-I mechanism with $\gamma \approx \gamma_{\max} = \sigma\Gamma$.
- Subsequent acceleration give a power-law tail with the canonical slope.