Summary of particle acceleration in relativistic jets

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Krakow, 22nd April 2015

~~Summary of~~ *Introduction to* particle acceleration in relativistic jets

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- Applied to relativistic shocks in late 80’s, and ultra-relativistic shocks in 00’s
- Why the delay?

Anisotropy

- Test-particle, power-law index depends on balance between energy gain and escape $\Rightarrow$ need to know angular distribution.
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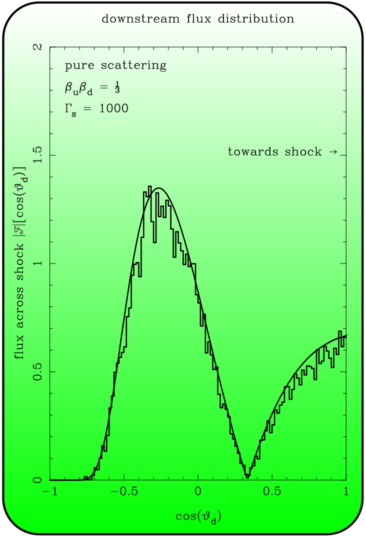
- Also a problem for nonrelativistic, perpendicular shocks.[a]

[a] Please ask afterwards!

Monte-Carlo

Comparison of MC/analytic angular distributions

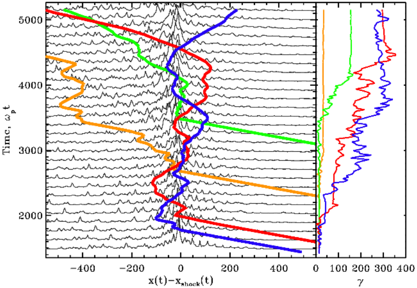
Achterberg et al MNRAS 328, 393 (2001)



2D PIC simulations, pair plasma

Spitkovsky (2008)
Martins et al (2009)

- Unmagnetized e^+e^- plasma
- Bulk $\Gamma \approx 30$
- Field generated by Weibel instability
- *Ab initio* demonstration of 1st order Fermi process at a shock front

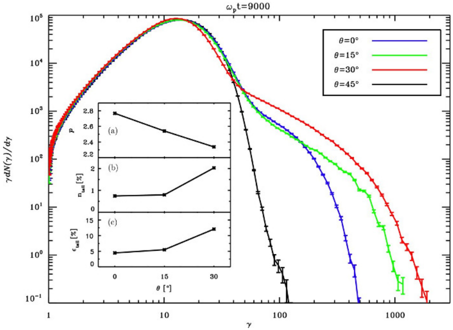


- 1% of particles in power-law tail
- Cut off at $\sim 100\times$ peak, growing in time
- $\mathrm{d}\ln N/\mathrm{d}\ln\gamma = -2.4 \pm 0.1$

Oblique shocks

Sironi & Spitkovsky (2009)

- Magnetized e^+e^- plasma
- Shock generated by magnetic reflection
- Qualitative agreement with test-particle picture



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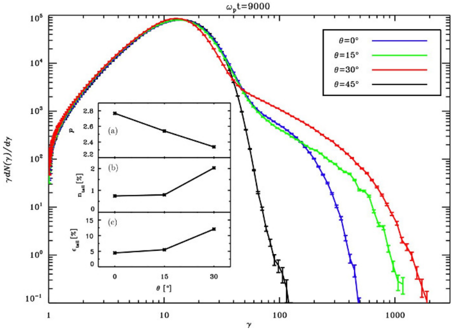

Issues remain concerning the generation and saturation of turbulence, acceleration rates, maximum energy etc.

Other dissipation mechanisms

- Dissipation requires short length/timescale structure.
- Velocity/density fluctuations ($\rightarrow$ internal shocks, shear)
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- Velocity/density fluctuations (→ internal shocks, shear)
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  - Called *reconnection* in an MHD model. Predicts hard spectral indices (Sironi 2014) and potentially very high energy cut-offs (Cerutti et al 2014)
  - Proceeds differently in an under-dense plasma (no flux freezing, electromagnetic *superluminal* modes present) (Arka, Mochol, Amano & JK, 2011 – 2013)

Superluminal wave damping

Three dimensionless jet parameters:

1. (Mass-loading)$^{-1}$ $\mu = L/\dot{M}c^2$ ($\equiv \sigma_{\rm M}$)
2. Magnetization σ_0 = Poynting flux/K.E. flux
3. *A parameter describing the jet composition: e/m*

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    - (Dimensionless luminosity/unit solid angle)$^{1/2}$:

      $a_0 = (4\pi L/\Omega_{\mathrm{s}})^{1/2} \left(e^2/m^2c^5\right)^{1/2}$

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Constraints/Estimates:

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

Waves in a conical $e^{\pm}$ jet/beam

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

Over-dense | Under-dense

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

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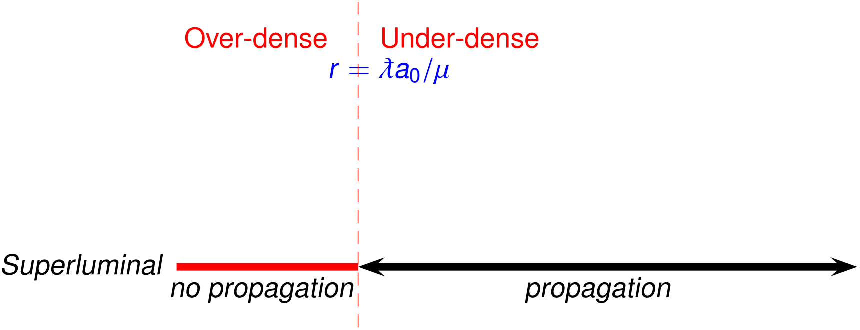

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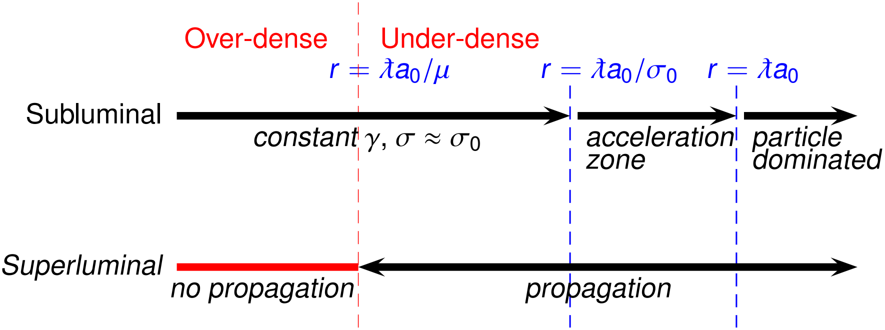

Waves in a conical $e^{\pm}$ jet/beam

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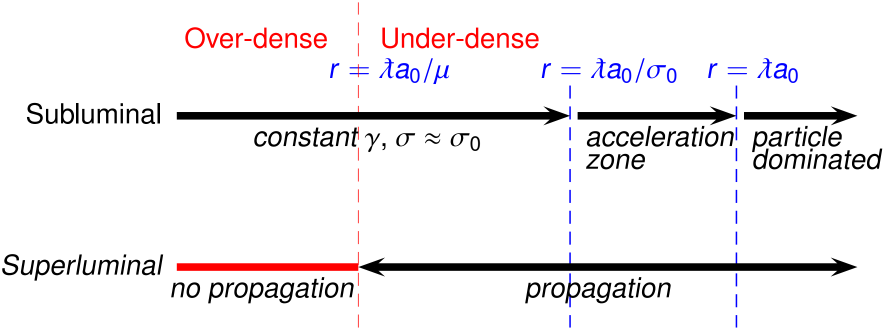

$\kappa_0 = 1$	4×10^{15}cm	10^{20}cm
$\kappa_0 = 1000$	4×10^{19}cm	10^{22}cm

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

Two-fluid simulations

Beyond MHD: simplest description that includes superluminal, electromagnetic modes is one with two charged fluids.

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Amano & Kirk ApJ (2013)

- Relativistic, finite temperature electron & positron fluids
- 1D in space, 3D in momentum and EM fields

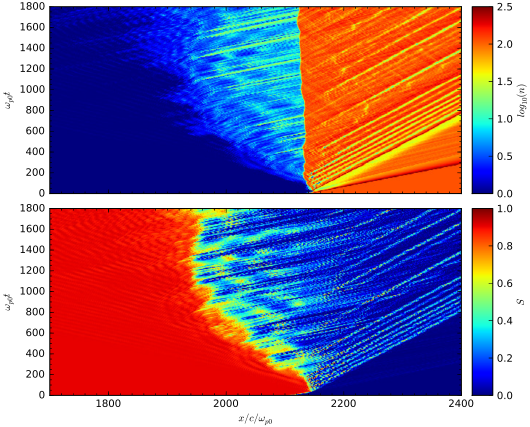
Two-fluid simulations

Beyond MHD: simplest description that includes superluminal, electromagnetic modes is one with two charged fluids.

Amano & Kirk ApJ (2013)

- Relativistic, finite temperature electron & positron fluids
- 1D in space, 3D in momentum and EM fields
- Initial conditions:
  - Left half: circularly polarized, cold, static shear, $\gamma = 40$, $\sigma = 10$, $\lambda_{\rm gyro}/\lambda = \sqrt{\sigma}\left(\omega/\omega_{\rm p}\right) \approx 4$
  - Right half: shocked (R-H conditions) unmagnetized plasma

Electromagnetically modified shock



$\Gamma = 40$

$\sigma = 10$

$\omega = 1.2\omega_{\rm p}$

Implications

- “Thermal” particles emit narrow band radiation in the precursor
  $\rightarrow$ GeV flares in γ-ray binaries (Mochol & JK, ApJ 2013)

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- Superluminal turbulence $\Rightarrow$ *wiggler* (Teraki et al ApJ 2015)

Implications

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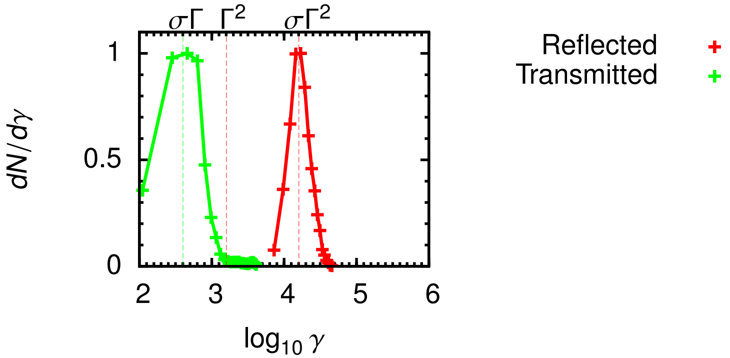
- Superluminal turbulence $\Rightarrow$ *wiggler* (Teraki et al ApJ 2015)

- A subshock remains: particles injected by reflection in the precursor wave subsequently undergo Fermi-type acceleration $\rightarrow s \approx 2.3$ recovered?

Injection at an electrodynamically modified shock front



$\Gamma = 40$, $\sigma = 10$, reflection probability $\approx 50\%$
(Giacchè & JK in prep)

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- Relativistic, MHD shocks accelerate particles in low σ flows (perpendicular shock geometry generic, anisotropy crucial.) Depends on microphysics of scattering.
- Relativistic reconnection a viable mechanism in high σ flows (but not discussed here!)
- Under-dense, high σ flows allow superluminal modes. Important for pulsars/PWN, maybe also for AGN. $\Rightarrow$ acceleration in *electromagnetically modified* shocks, potentially observable signatures.

Stationary solution

Separation of variables:

$$f(z,\vec{p}) = p^{-s}\sum_i c_i \mathrm{e}^{\Lambda_i z\omega_{\mathrm{g}}/v} Q_i(\mu,\phi)$$

$$\Lambda_i\left(\hat{v}_z - u\right)Q_i = \left\{-\frac{\partial}{\partial\phi} + \frac{1}{2\eta}\left[\frac{\partial}{\partial\mu}\left(1-\mu^2\right)\frac{\partial}{\partial\mu} + \frac{1}{1-\mu^2}\frac{\partial^2}{\partial\phi^2}\right]\right\}Q_i$$

($\hat{v}_z = \sqrt{1-\mu^2}\sin\phi$, $\eta = \omega_{\mathrm{g}}/\nu_{\mathrm{coll}}$ is the inverse “collisionality”.)

- Similar to method used for relativistic shocks (ApJ 2000).
- But two-parameter (η, u), two-dimensional (μ, ϕ) and non self-adjoint problem.
- Approximate by retaining only the ‘leading’ upstream eigenfunction.

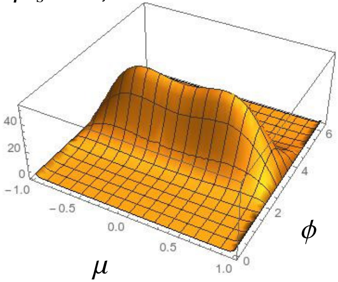
Approximate analytic solution for $u_\mathrm{s} \sim 1/\eta \sim \epsilon \ll 1$

- $Q = \mathrm{e}^{\Lambda v \sqrt{1-\mu^2}\cos\phi}\,\mathrm{Ps}_0^0\left(\mu, -\Lambda^2/2\right)$
  Ps_n^m: angular, oblate, spheroidal wave function.
- Power-law index fixed by b.c.'s, series in ηu:

$$s = \frac{3r}{r-1} + \frac{9\,(r+1)}{20r(r-1)}\eta^2 u_\mathrm{s}^2 + \mathrm{O}\left(\eta^4 u_\mathrm{s}^4\right)$$

(r = compression ratio)
M. Takamoto & JK, ApJ submitted

Leading eigenfunction, $\eta u_\mathrm{s} = 2$,



Anisotropic at order ϵ^0, as suggested by Schatzman (1963).