Particle Acceleration, Shocks, Reconnection. . .

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Blazar Variability, École Polytechnique, 24th April 2008

1st order Fermi process at shocks

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$$\Rightarrow \qquad \frac{\mathrm{d}N}{\mathrm{d}\gamma} \propto \gamma^{2-s}$$

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- Solve transport equation Kirk et al (2000)
  - Directional dependence of angular diffusion *and* zeroth-order propagator in distance z from shock front
  - For parallel shock, and for weak magnetization, *free-particle propagator* ($\mu = \hat{\vec{v}} \cdot \hat{\vec{z}}$):

$$(u + \mu)\frac{\partial f}{\partial z} \quad = \quad \frac{\partial}{\partial \mu} D_{\mu\mu} \frac{\partial f}{\partial \mu}$$

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- Prescribe a scattering law and propagator and apply Monte-Carlo Bednarz & Ostrowski (1998); Achterberg et al (2001); Baring & Stecker (2007)
- Prescribe a “realistic” turbulent magnetic field and apply Monte-Carlo Niemic, Ostrowski & Pohl (2006)

A perception of reality

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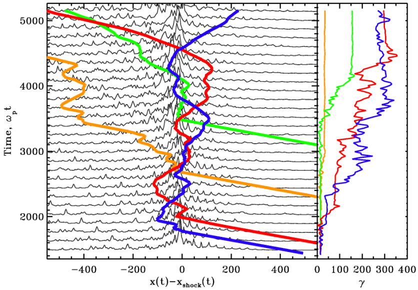
2D P.I.C. simulations
Spitkovsky arXiv:0802.3216

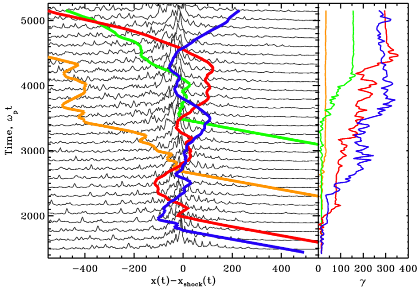
- Unmagnetized e^+e^- plasma
- Bulk $\Gamma \approx 30$
- Field generated by Weibel instability



A perception of reality

2D P.I.C. simulations
Spitkovsky arXiv:0802.3216

- 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
- $s = 4.4 \pm 0.1$

Analytic approximations

- Transport described by an angular diffusion coefficient $D_{\mu\mu}$
- Expansion in eigenfunctions Q_J of

$$\left[\frac{\mathrm{d}}{\mathrm{d}\mu} D_{\mu\mu} \frac{\mathrm{d}}{\mathrm{d}\mu} - \Lambda_J (u + \mu)\right] Q_J = 0$$

converges rapidly if upstream eigenfunctions used to represent f.

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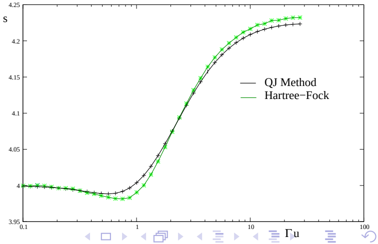
- Numerical evaluation straightforward
- Variational principle
  $\longrightarrow$ ground state eigenfunction
  $\longrightarrow$ analytic approximation for s

Dempsey & Kirk (2008)



Hysteresis

Hysteresis

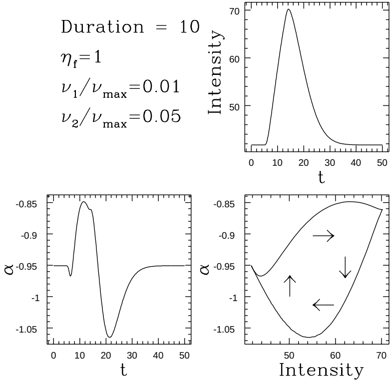
Cooled particles: soft lag

Duration = 10

$\eta_f = 1$

$\nu_1/\nu_{max} = 0.01$

$\nu_2/\nu_{max} = 0.05$



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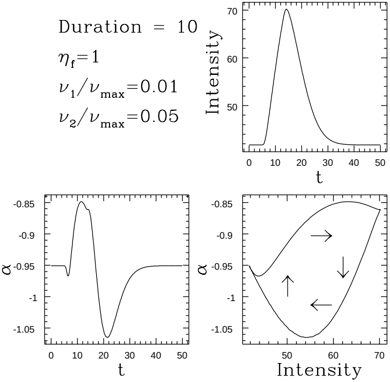
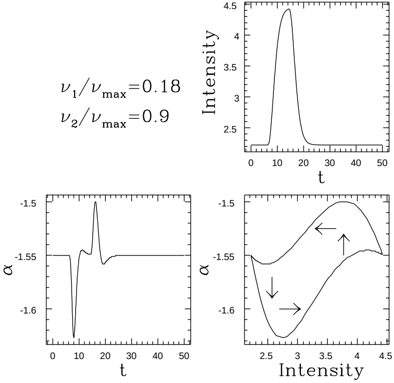


Accelerating particles: hard lag



Broad-band emission

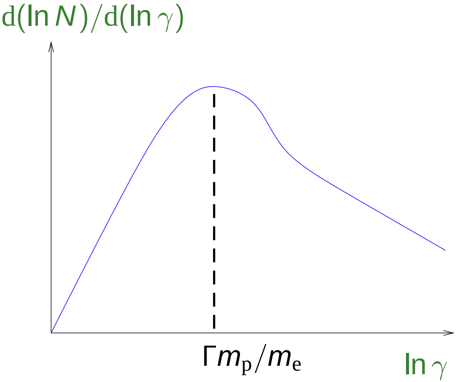
Relativistic shock front:

- Energy per particle upstream $\Gamma m_{\mathrm{p}} c^2/2$
- Downstream $\epsilon_B \sim 1\%$ into magnetic field
- Temperature $T \approx \Gamma m_{\mathrm{p}} c^2/2k_{\mathrm{B}}$
- "Thermal" electron distribution

$$\frac{\mathrm{d}N}{\mathrm{d}\gamma} \propto \gamma^2 \exp\left(-\gamma m_{\mathrm{e}} c^2/k_{\mathrm{B}} T\right)$$

- Accelerated electrons

$$\frac{\mathrm{d}N}{\mathrm{d}\gamma} \propto \gamma^{-2.2} \quad \text{for } \gamma \gg k_{\mathrm{B}} T/m_{\mathrm{e}} c^2$$



Electrons at shock

- At low freq. emissivity dominated by electrons with $\gamma = \Gamma m_p/2m_e$
- equivalent to monoenergetic distribution
- At high freq. $\alpha = 1.1$ (cooled distribution)

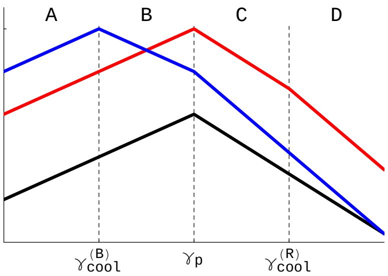
Double power-law injection

Low energy $Q \propto \gamma^{p_1}$
High energy $Q \propto \gamma^{p_2}$

Black: injected distribution

Blue: Particles at $\gamma_{\rm peak}$ have time to cool within source

Red: Particles at $\gamma_{\rm peak}$ *do not* have time to cool within source



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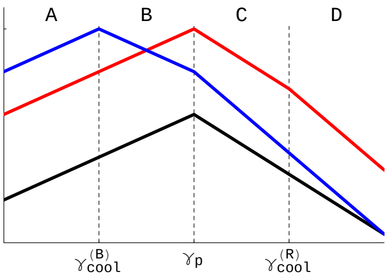

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Maxwellian: $p_1 = 2$
Shock acceleration: $p_2 = -2.2$

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Observed brightness temperature

Standard theory, weak absorption

$$T_\mathrm{B} \quad = \quad 1.2 \times 10^{14} \left(\frac{\mathcal{D}_{10}^6 \xi}{(1+z)^6} \right)^{1/5} \left(\frac{1 - \mathrm{e}^{-\tau_\mathrm{s}}}{\tau_\mathrm{s}^{1/5}} \right) \nu_\mathrm{max14}^{2/15} \nu_\mathrm{GHz}^{-1/3} \,\mathrm{K}$$

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- $\tau_{\rm s}$: optical depth to synchrotron self-absorption at $\nu_{\rm GHz}$
- $\nu_{\rm max14}$: characteristic frequency of synchrotron radiation in units of 10^{14} Hz (flat spectrum up to this frequency)
- ξ: “catastrophe” parameter ($\approx \gamma^2 \tau_{\rm T}$) $\lesssim 1$

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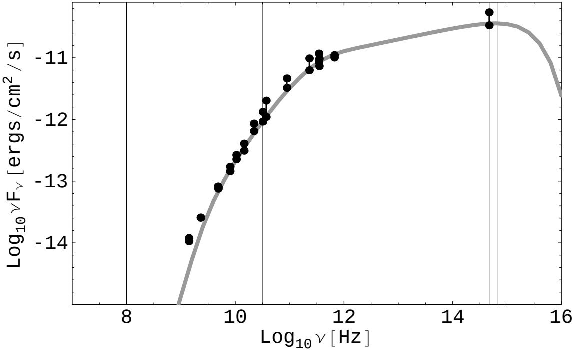
Intrinsic degree of circular polarisation

$$r_{\rm c} \;=\; 0.019\times\left(\frac{(1+z)\tau_{\rm s}}{\mathcal{D}_{10}\xi}\right)^{1/5}\nu_{\rm max14}^{1/5}\,\cot\theta$$

SSC model for S5 0716 +71



Parameters

$\mathcal{D} = 65$

$\gamma_{\rm peak} = 700$

$p_1 = 2$

$p_2 = -2.6$

$B = 2.7\,\mathrm{mG}$

$n_e = 0.3\,\mathrm{cm}^{-3}$

$R = 0.17\,\mathrm{pc}$

$\Delta\theta = 38\,\mu\mathrm{arcsec}$

Tsang & Kirk (2007); data from Ostorero et al (2006)

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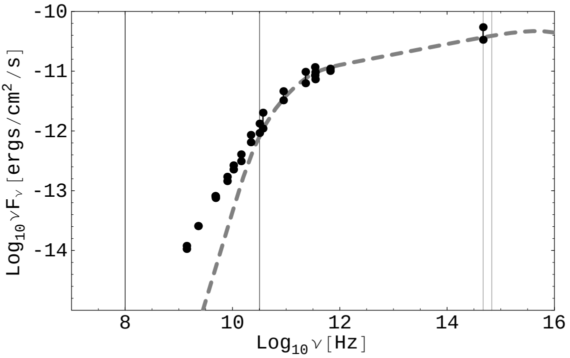


Parameters

$\mathcal{D} = 30$

$\gamma_{\rm peak} = 240$

$p_1 = 2$

$p_2 = -2.6$

$B = 35\,\mathrm{mG}$

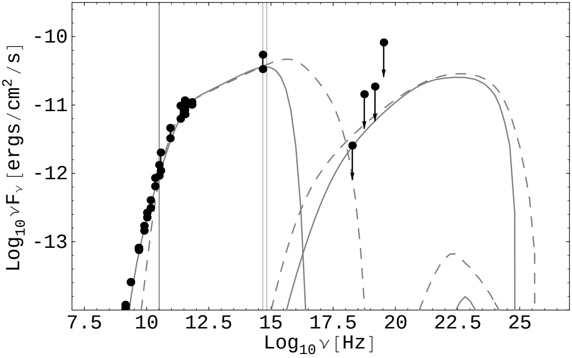
$n_{\rm e} = 3\,\mathrm{cm}^{-3}$

$R = 0.08\,\mathrm{pc}$

$\Delta\theta = 18\,\mu\mathrm{arcsec}$

Tsang & Kirk (2007); data from Ostorero et al (2006)

SSC model for S5 0716 +71



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Collimation or dissipation?

- For relativistic, radial flow

$$\begin{aligned}\sigma &= \frac{\text{magnetic enthalpy density}}{\text{particle enthalpy density}}\\ &= \text{constant}\end{aligned}$$

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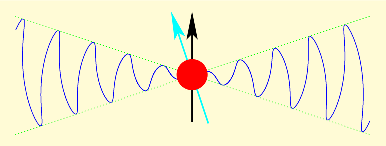
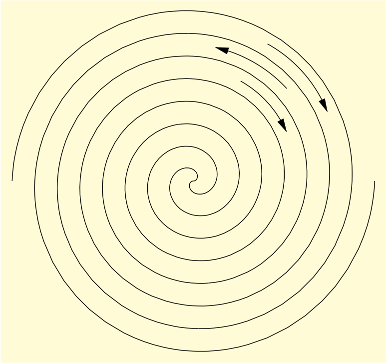
- Nonradial flow: acceleration of jet possible
- Changing magnetic polarity: dissipation possible

Sheet geometry

Oblique, split-monopole solution Bogovalov 1999

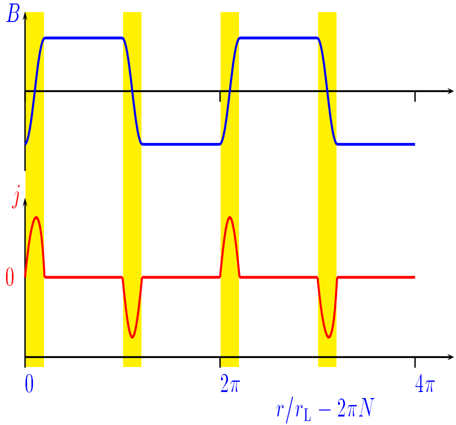


Meridional plane



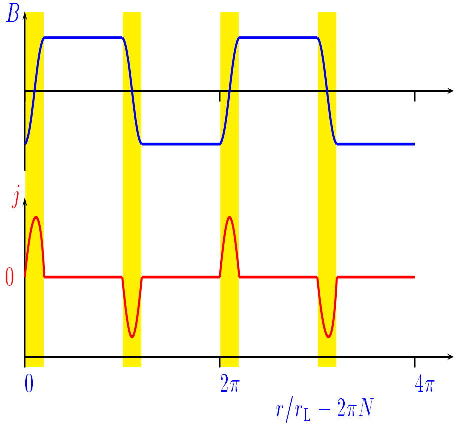
Equatorial plane

Sheet structure



Properties

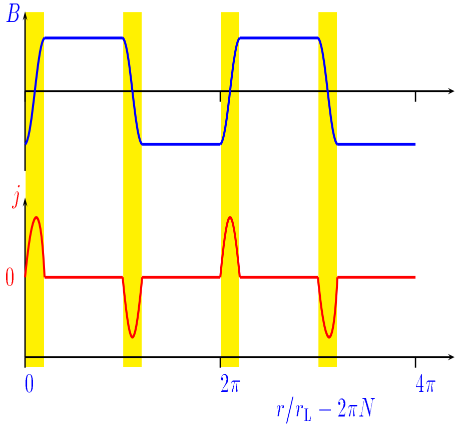
Sheet structure



Properties

- Thermal pressure balances magnetic pressure
- $+$ and $-$ charges counterstream (drift) in sheet

Sheet structure



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- Solutions unstable (tearing, kink. . .)

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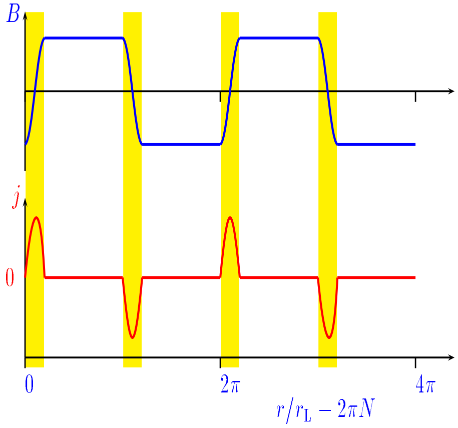

What controls the dissipation rate?

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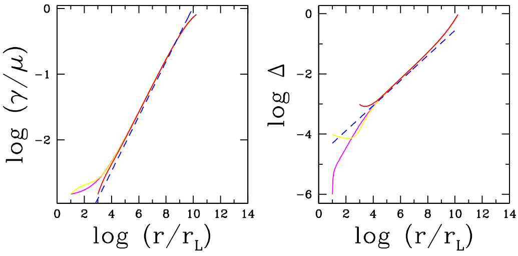
- Gradual, complete dissipation impossible if too few particles available: $\Gamma < 3\times$ *multiplicity*

  Lyubarsky & Kirk 2001

Slow dissipation



$$\Gamma \propto r^{5/12}$$

$$\frac{r_{\rm max}}{r_{\rm L}} = \Gamma_{\rm max}^{4/5} \hat{L}^{3/10}$$

$$\hat{L} = L\left(\frac{\pi^2 e^2}{m^2 c^5}\right)$$

$$= 1.5 \times 10^{22}$$

(for Crab)

Relativistic tearing mode

- Magnetic energy $\Rightarrow$ heat
- Hot plasma expands
- Flow accelerates
- Timescale dilates

Kirk & Skjæraasen 2003

Conclusions

- 1st order Fermi process at relativistic shocks alive and well. Asymptotic spectral index $s \approx 4.3$ ($\mathrm{d}\ln N/\mathrm{d}\ln\gamma = -2.3$) Not unrealistic - FR I radio galaxies Laing et al 2008 arXiv:0801.0154
- Models with predictive power: hard and soft lags expected. Radiation mechanism uncertain but testable. High brightness temperature and intrinsic circular polarisation possible.
- Problems e.g., very high Doppler factors, hard spectra, suggest alternatives: shear acceleration, second order acceleration. . .
- Highly magnetized flows: first order Fermi process killed. Dissipative current sheets attractive, but predictive power of current models limited.