Radiative Signatures of Relativistic Shocks

John Kirk   Brian Reville

Max-Planck-Institut für Kernphysik
Heidelberg, Germany

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PIC phenomenology

Magnetized vs *Unmagnetized* dichotomy
(relativistic e^+-e^- plasma, bulk Lorentz factor $\bar{\gamma}$
magnetization parameter $\sigma = B^2/(4\pi\bar{\gamma}nmc^2)$)

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- Reflection at magnetic barrier
- Synchrotron maser instability
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- Streaming instability (rel. Bell, Weibel...)
- Filaments/clumps on small length scale $\lambda \sim \bar{\gamma}^{1/2}c/\omega_{\rm p}$
- Decay, merging?

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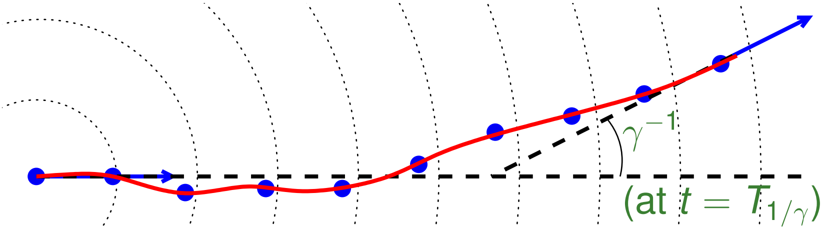
Is there a radiative signature?

Magneto-brems., diffuse synchrotron, jitter...

Incoherent (single particle) radiation determined by trajectory



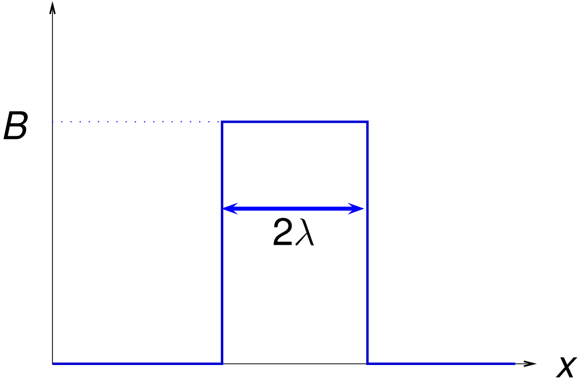
Fundamental concept: formation time T:

- Classically: time for particle to lag $\sim$ 1 wavelength behind wavefront
- QM: time needed to create photon

Formation length can be large: $T = 2\gamma^2 c/\omega$, for $T < T_{1/\gamma}$

Idealized scatterer

Strength parameter: $a = \lambda eB/mc^2$ $(\delta\theta = 2a/\gamma)$



Magnetized: $a \sim \bar{\gamma}$ Unmagnetized: $a \sim \bar{\gamma}\sigma^{1/2}$

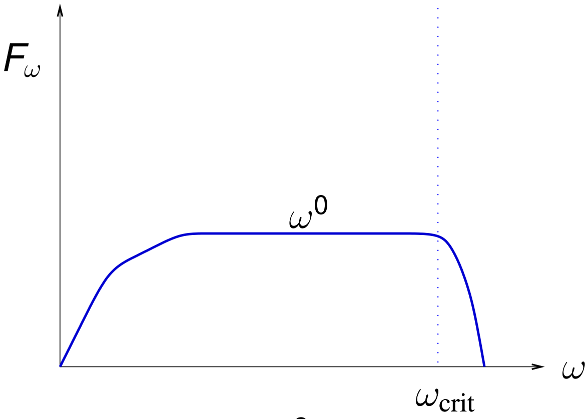
Spectrum: $a \gg 1$

- Fields constant over a formation length
- Can define a local emissivity
- 'Synchrotron' radiation (independent of whether E or B is responsible)
- Integrated over angle, low frequency spectrum is $\omega^{1/3}$, because:

$$\omega\left(t - \frac{1}{c}\left|\boldsymbol{r}(t) - \boldsymbol{r}(0)\right|\right) \approx \frac{\omega}{2\gamma^2}t - \frac{\omega c^2\kappa^2}{24}t^3$$

Spectrum: $a \ll 1$

$\delta\theta < \gamma^{-1}$, $T < T_{1/\gamma}$, formation time $T = 2\gamma^2/\omega$



$$\omega_{\rm crit} = \gamma^2 c/\lambda$$

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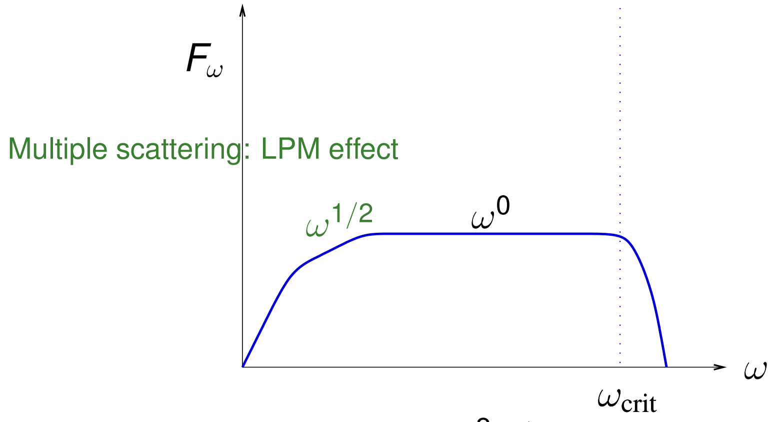

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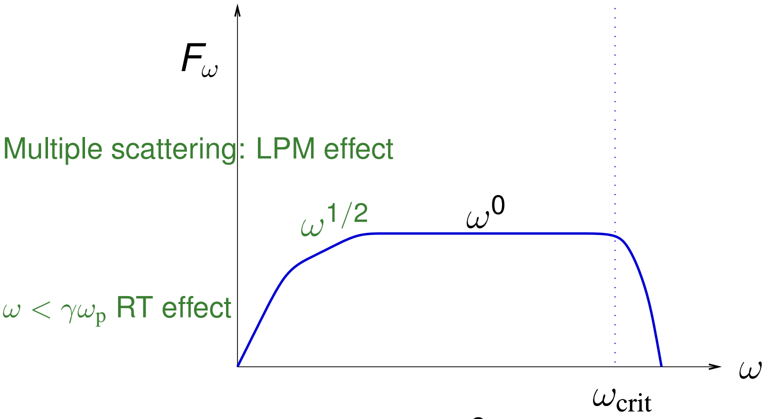
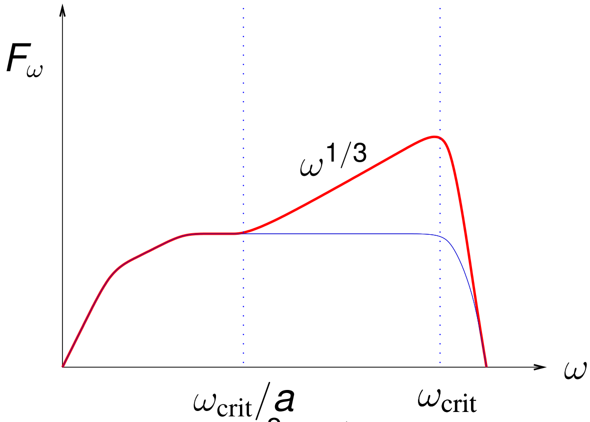


$$\omega_{crit} = \gamma^2 c/\lambda$$

Spectrum: $\gamma \gg a > 1$

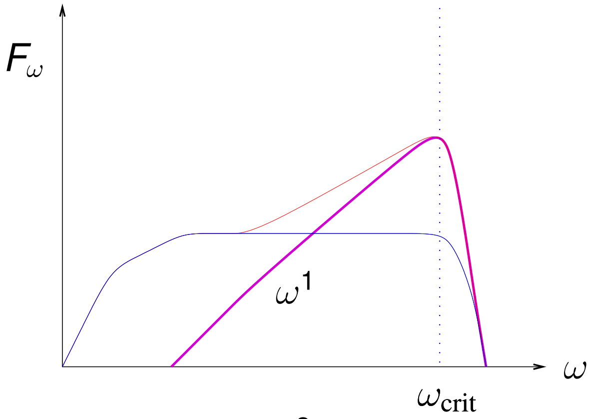
Local, instantaneous emission for $T < \lambda/c$



$$\omega_{\rm crit} = \gamma^2 eB/mc$$

Spectrum: $a \ll 1$ coherent scatterers

$T = 2\gamma^2/\omega$ For $\lambda_{\rm wavetrain} > cT > \lambda$ analogous to I.C. scattering



$$\omega_{\rm crit} = \gamma^2 c/\lambda$$

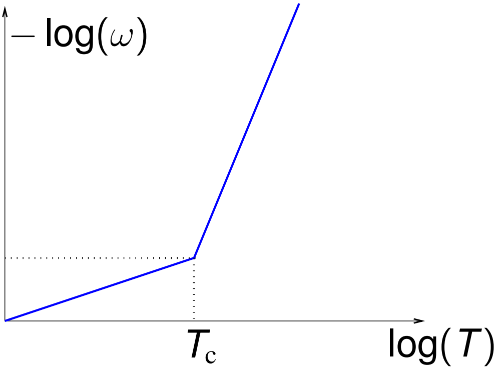
Numerical approach

Instantaneous power (integrated over angles) (Schwinger 1949):

$$P(t) = -\frac{e^2\omega}{2\pi c^2}\int_{-\infty}^{\infty} \mathrm{d}\tau [1 - \boldsymbol{\beta}(t+\tau)\cdot\boldsymbol{\beta}(t)] \frac{\sin(\omega|\tau| - \omega\Delta)}{\Delta} + \ldots$$

$\Delta = |\boldsymbol{r}(t+\tau) - \boldsymbol{r}(t)|/c,$

$\delta\theta = 1/\gamma$ at $\tau = T_\mathrm{c}$



Maximum energy, maximum frequency

- Random small-angle deflections:

$$\Delta\theta = 2a/\gamma \quad (\propto B)$$

- Number of scatterings needed to isotropize:

$$N_{\rm scatt} \approx (\pi/\Delta\theta)^2$$

- Energy loss per scattering:

$$\Delta\gamma/\gamma = 2\alpha_{\rm f} ab\gamma/3 \propto B^2$$

$(b = B/B_{\rm crit} = B/(4.4 \times 10^{13}\,{\rm G}))$

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Maximum energy, maximum frequency

- Acceleration/confinement, requires isotropization rate faster than energy loss rate:

$$N_{\rm scatt}\Delta\gamma/\gamma < 1$$
$$\Rightarrow \gamma < 10^6\left(n/1\,{\rm cm}^{-3}\right)^{-1/6}$$

- Maximum energy of radiated photon (co-moving frame):

$$\hbar\omega_{\rm max} = \begin{cases} 40\left(n/1\,{\rm cm}^{-3}\right)^{1/6}\bar{\gamma}^{1/6}\,{\rm eV} & \text{for } a \ll 1 \\ 40a\left(n/1\,{\rm cm}^{-3}\right)^{1/6}\bar{\gamma}^{1/6}\,{\rm eV} & \text{for } \gamma \gg a > 1 \\ & (\textit{synchrotron}) \end{cases}$$

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(Cf. *Bohm diffusion*, $a \approx \gamma$, $\hbar\omega_{\mathrm{max}} \sim 100\,\mathrm{MeV}$)

Two kinds of scatterers?

Isotropization (large λ, small B) and radiation (small λ, large B) by different scatterers?

- Define

$$\lambda_{\rm losses} = \frac{\langle B^2\lambda\rangle}{\langle B^2\rangle}$$

$$\lambda_{\rm isotrop}^{-2} = \left\langle \frac{1}{B^2\lambda^2}\right\rangle \langle B^2\rangle$$

- Maximum energy increased if $\lambda_{\rm isotrop} \gg \lambda_{\rm losses}$:

$$\hbar\omega_{\rm max} \rightarrow \left(\lambda_{\rm isotrop}/\lambda_{\rm losses}\right)^{4/3} \hbar\omega_{\rm max}$$

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Summary

- 1st order Fermi requires scatterers with $a \ll 1$
- Associated synchrotron/jitter radiation is in optical/UV independent of B (but $\nu_{\mathrm{max}} \propto \mathrm{density}^{1/6}$)
- Low freq. spectrum $F_\nu \propto \nu^0$ for uncorrelated, $F_\nu \propto \nu^1$ for correlated filaments/clumps, with LPM or Razin-Tsytovich suppression.
- In magnetized case, ν_{max} increases $\propto a$, low freq. spectrum is synchrotron-like: $\nu^{1/3}$
- $F_\nu \propto \nu^1$ in X-rays requires two populations of scatterers, one for acceleration/confinement, one for radiation (e.g., Inverse Compton on soft photons)