# Possible regimes of synchrotron and inverse Compton radiation in relativistic flows and shocks

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# Outline

# Synchrotron spectrum

## Uniform magnetic field

Synchrotron spectral power: $P_\omega = \frac{\sqrt{3}}{2\pi}\frac{e^3 B}{m_e c^2} F\left(\frac{\omega}{\omega_c}\right)$

Here

$$\omega_c = \frac{3}{2}\gamma^2 \frac{eB}{m_e c}$$

$$F(x) = x\int_x^\infty K_{5/3}(\xi)\,\mathrm{d}\xi$$

$K_{5/3}(\xi)$ is modified Bessel function of the second kind

pitch angle $\pi/2$

# Synchrotron spectrum

## Turbulent magnetic field

- Averaging over pitch angles and local magnetic field strengths is needed
- Gaussian distribution of local magnetic field strengths and isotropic distribution over pitch angles is a natural option

## Gaussian-distributed magnetic field

Photon number per spectral interval:

$$N_\omega \equiv \frac{P_\omega}{\hbar\omega} = \frac{\alpha}{3}\frac{1}{\gamma^2}\left(1+\frac{1}{x^{2/3}}\right)\exp\left(-2x^{2/3}\right)$$

Here $x = \frac{\omega}{\omega_0}$, $\omega_0 = \frac{4}{3}\gamma^2\frac{eB_{\rm rms}}{m_e c}$

Derishev & Aharonian arXiv:1907.11663

# Synchrotron peak position

## Balance of acceleration and radiative losses

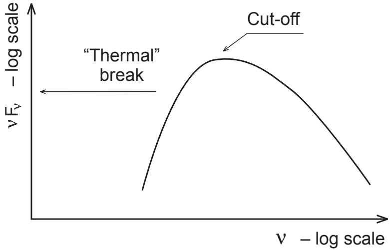
- Electron acceleration rate $\dot{\epsilon}_{acc} = eE_{eff}\,c \equiv \eta eBc$

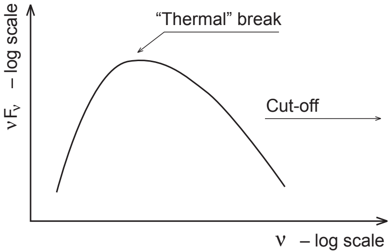
  (in case of shock acceleration $\eta \simeq U_{sh}^2/c^2$)

- Power of synchrotron radiation $\dot{\epsilon}_{loss} = \frac{4}{9}\gamma_e^2 \left(\frac{e^2}{m_e c^2}\right)^2 B^2 c$

- balance $\dot{\epsilon}_{loss} = \dot{\epsilon}_{acc} \quad \Rightarrow \quad \epsilon_{sy} \simeq \eta \frac{m_e c^2}{\alpha}$

# Synchrotron peak position




- acceleration efficiency

$$\eta \sim \frac{\lambda_B}{r_g} \ll 1$$

- For $\lambda_B < r_g/\gamma$ transition to undulator regime with $\omega \propto \lambda_B^{-1}$

"Minimal heating" scenario: small-scale magnetic field decays and heats electrons

Derishev, ApSS 2007

# Anticipated effective electric field

(quick and dirty estimate)

## Magnetic field decay time

- decay time (kinetic damping): $\tau \sim \frac{1}{\omega_p}\left(\frac{\lambda_{\rm B}\omega_p}{c}\right)^3$
- dynamical balance: $\tau \sim R/V$

## Maxwell equation for electric field

$$\nabla \times \vec{E} = -\frac{1}{c}\frac{\partial \vec{B}}{\partial t} \quad \Rightarrow \quad \eta \sim \frac{\lambda_{\rm B}}{c\tau}$$

## Relate turbulence spatial scale to plasma frequency

$$\lambda_{\rm B} \sim \left(\frac{Rc^3}{\omega_p^2 V}\right)^{1/3} \quad \Rightarrow \quad \eta \sim (\omega_p \tau)^{-2/3}$$

# Application to real sources

## Approximate relations

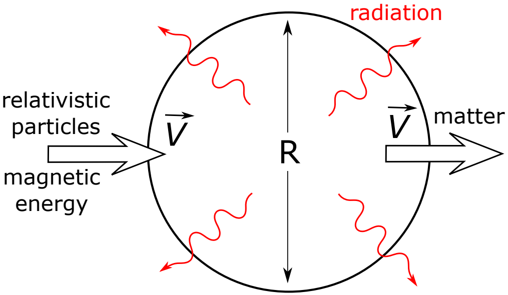
- Plasma frequency: $\omega_p^2 = \dfrac{4\pi e^2 N}{m_p}$
- Energy density: $w \simeq NT$
- Temperature: $T \simeq m_p V^2$
- Luminosity: $L \simeq 4\pi R^2 w V$

## Order-of-magnitude estimate

$$\eta \sim \left(\frac{m_p^2 c^5}{e^2}\right)^{1/3} \frac{(V/c)^{5/3}}{L^{1/3}} \simeq 1.4 \times 10^{-5}\, \frac{(V/c)^{5/3}}{L_{38}^{1/3}}$$

that is, $\epsilon_{sy} \sim 1\ \mathrm{keV} \times (V/c)^{5/3}\, L_{38}^{-1/3}$

# A "spherical cow" emitting zone




Energy inflow rate:

$$\dot{E}_{el} = E_{el} \times V/R$$

Energy outflow rate:

$$\dot{E}_{rad} = E_{rad} \times c/R$$

Fast cooling balance: $\dot{E}_{rad} = \dot{E}_{el} \quad \Rightarrow \quad e_{rad} = (V/c)\, e_{el}$

Synchrotron power: $\dot{P}_{sy} = \frac{4}{3}(\gamma^2 - 1)\sigma_{\mathrm{T}}\, e_{\mathrm{B}}\, c$

Inverse Compton power: $\dot{P}_{IC} = \frac{4}{3}(\gamma^2 - 1)\kappa_{\mathrm{KN}}\sigma_{\mathrm{T}}\, e_{sy}\, c$

# Relative efficiencies

Compton $y$ parameter $y \equiv \frac{4}{3}(\gamma^2 - 1)\sigma_{\rm T} n_e R$

## Synchrotron radiation

energy flux: $F_{sy} \simeq \frac{2}{3}(\gamma^2 - 1)\sigma_{\rm T} n_e e_{\rm B} cR \simeq \frac{1}{2} y e_{\rm B} c$

energy density: $e_{sy} \simeq \frac{\Lambda}{2} y e_{\rm B}$ ($\Lambda$ – geometrical factor)

## self-Compton radiation

energy flux: $F_{IC} \simeq \frac{1}{2}\kappa_{\rm KN} y e_{sy} c \simeq \kappa_{\rm KN} \frac{\Lambda}{4} y^2 e_{\rm B} c$

## Radiative efficiency (generalization of Sari, Narayan & Piran 1996)

synchrotron efficiency: $\epsilon_{sy} \equiv F_{sy}/F \simeq y \left(\frac{c}{V}\right) \epsilon_{\rm B}$

self-Compton efficiency: $\epsilon_{IC} \equiv F_{IC}/F \simeq \kappa_{\rm KN} \frac{\Lambda}{2} y \epsilon_{sy}$

overall efficiency: $\epsilon_{rad} = \epsilon_{sy} + \epsilon_{IC} \simeq (y + \kappa_{\rm KN} \frac{\Lambda}{2} y^2) \left(\frac{c}{V}\right) \epsilon_{\rm B}$

# Synchrotron-self-Compton

Consider injection $\dot{N}_\gamma \propto \left(\frac{\gamma_b}{\gamma_b + \gamma}\right)^p, \quad p > 2$

$\gamma_c$ is the minimal Lorentz factor such that electrons cool radiatively

$$\gamma_0 \simeq \left(\frac{4.4 \times 10^{13}\ \mathrm{G}}{B}\right)^{1/3}$$

is the Lorentz factor such that electrons comptonize their own synchrotron radiation at the border of Klein-Nishina regime

# Synchrotron-self-Compton regimes

## Slow cooling

- $\gamma_c > \gamma_b$ and $p > 3$ or $\gamma_c$ is very large
- trivial (but may be technically complex) problem

## Fast cooling

- $\gamma_c < \gamma_b$
- synchrotron component peaks at $\omega_{sy}^{peak} \simeq \gamma_b^2 \dfrac{eB}{m_e c}$
- Thomson regime: $\omega_{\mathrm{IC}}^{peak} \simeq \gamma_b^2\, \omega_{sy}^{peak}$
- Klein-Nishina regime: $\hbar\omega_{\mathrm{IC}}^{peak} \lesssim \gamma_b\, m_e c^2$

## Incomplete cooling

- $\gamma_c > \gamma_b$ and $p < 3$
- model-dependent derivation of spectral shapes

# Fast cooling parameter space

## Thomson regime

Compton dominance $\eta_{IC} \equiv F_{IC}/F_{sy} \sim y$

## Klein-Nishina regime

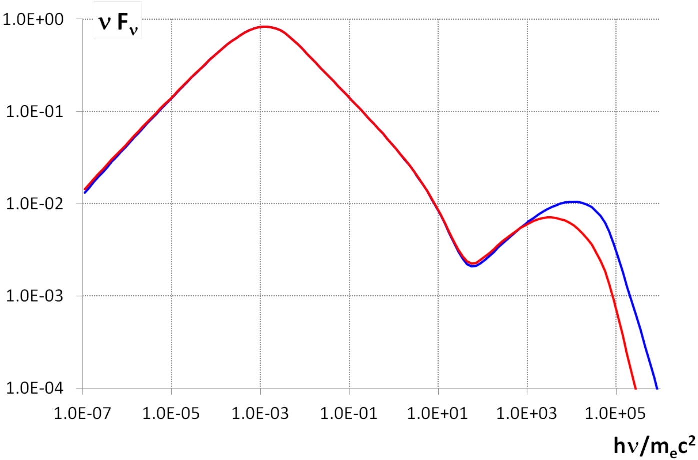
Compton dominance $\eta_{IC} < (\gamma_0/\gamma_b)^{3/2}\, y$

Two-photon self-absorption of IC radiation is inevitable

- small Compton dominance $(y \ll (\gamma_b/\gamma_0)^{3/2}$ for $\gamma_c \lesssim \gamma_0)$
- large Compton dominance $(y \gtrsim (\gamma_b/\gamma_0)^{3/2}$ for $\gamma_c \lesssim \gamma_0)$

# What happens due to self-absorption

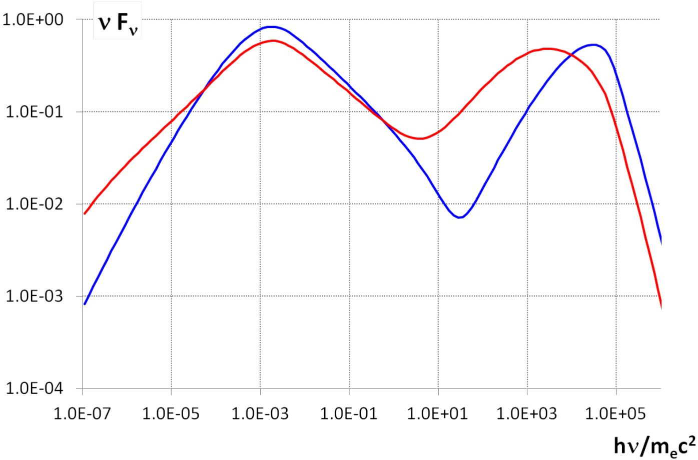
# Self-absorbed SSC
(small Compton dominance)




ignoring two-photon absorption
two-photon absorption taken into account

# Self-absorbed SSC

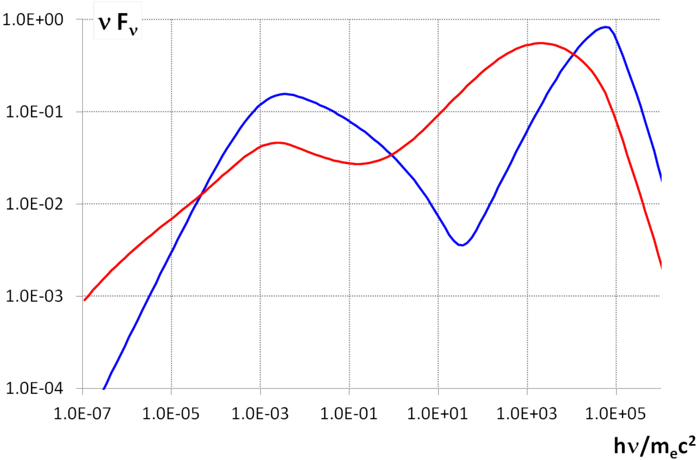
(medium Compton dominance)




ignoring two-photon absorption

two-photon absorption taken into account

# Self-absorbed SSC
(large Compton dominance)




ignoring two-photon absorption
two-photon absorption taken into account

# What happens due to self-absorption

## Small Compton dominance

- Synchrotron peak stays unchanged
- IC peak goes down in amplitude and shifts to smaller frequency

## Large Compton dominance

- IC peak broadens and shifts to smaller frequency
- Synchrotron peak goes down in amplitude
- Synchrotron luminosity goes up at frequencies well below the peak

# Complications for real sources

- Real sources don't have to be stationary or quasi-stationary
- There is no clear picture of acceleration mechanism

  $\Rightarrow$ we can only guess injection function
- Two-photon absorption may trigger converter acceleration

  $\Rightarrow$ there is back reaction from emission to acceleration
- In extreme accelerators even synchrotron radiation may be two-photon absorbed