High Energy Radiation Processes

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Outline

What this talk is about

Malcolm's Talk: Radiation Processes in High Energy Astrophysics

A Physical Approach with Applications

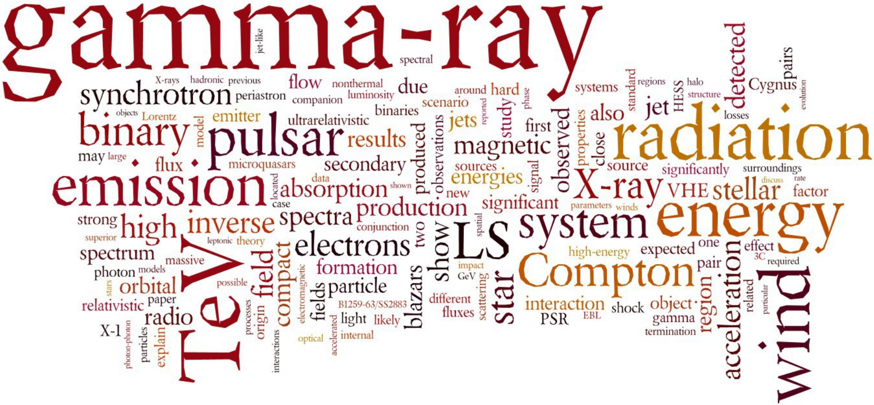
Bremsstralung, Synchrotron, inverse Compton (Thomson limit)

This talk: High Energy Radiation Processes

One Zone Modelling

Synchrotron, inverse Compton (Klein-Nishina limit)

The talk is biased towards



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Particle Distribution

Microscopical Description

$$\mathrm{d}N(q_i, p_i, t) = f(q_i, p_i, t)\mathrm{d}q_i\mathrm{d}p_i$$

- f is the distribution function
- q_i and p_i are some coordinates in the phase space

$$f = \text{e.g.} \quad \frac{\mathrm{d}N}{\mathrm{d}V} \quad \text{or} \quad \frac{\mathrm{d}N}{\mathrm{d}^3x\mathrm{d}^3p}$$

- One Zone Modeling typically implies

$$f = \frac{\mathrm{d}N}{\mathrm{d}E}$$

Particle Distribution

Microscopical Description

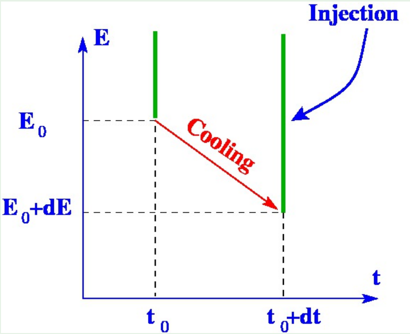
- Boltzmann Equation

$$\frac{\partial f}{\partial t} + \mathbf{v}\frac{\partial f}{\partial \mathbf{r}} + \mathbf{F}\frac{\partial f}{\partial \mathbf{p}} = \left[\frac{\partial f}{\partial t}\right]_{\rm col}$$

- Collision integral $\left[\frac{\partial f}{\partial t}\right]_{\rm col}$ accounts for many processes: *particle injection, acceleration, scattering, energy losses, etc*
- In the case of injection/cooling problems, the problem may be significantly simplified under the *continue loss approximation*

Significant simplification in the case of energy losses

Cont. Loss Approx.



Distribution function & Injection

$\mathrm{d}N = f(E,t)\mathrm{d}E \quad \mathrm{d}N = q(E,t)\mathrm{d}E\mathrm{d}t$

$$F(E,t) = \int_E^\infty f(E',t)\mathrm{d}E'$$

$$F(E+\dot{E}\mathrm{d}t, t+\mathrm{d}t) =$$

$$F(E,t) + \mathrm{d}t \int_E^\infty q(E',t)\mathrm{d}E'$$

Fokker-Planck Equation

$$\frac{\partial f}{\partial t} + \frac{\partial(\dot{E}f)}{\partial E} = q(E,t)$$

Significant simplification in the case of energy losses

$$F(E+\dot{E}\mathrm{d}t, t+\mathrm{d}t) = F(E,t) + \mathrm{d}t \int_E^\infty q(E',t)\mathrm{d}E'$$

$$F(E,t) + \frac{\partial F}{\partial E}\dot{E}\mathrm{d}t + \frac{\partial F}{\partial t}\mathrm{d}t = F(E,t) + \mathrm{d}t \int_E^\infty q(E',t)\mathrm{d}E'$$

$$\frac{\partial}{\partial E} \Longrightarrow$$

accounting for $\frac{\partial F}{\partial E} = -f$ $\quad \frac{\partial}{\partial E}\int_E^\infty q(E',t)\mathrm{d}E' = -q$

$$\frac{\partial f}{\partial t} + \frac{\partial(\dot{E}f)}{\partial E} = q(E,t)$$

Particle Energy Distribution

Fokker-Planck Equation Solution

$$f(E,t) = \frac{1}{\dot{E}} \int_{E}^{E_{\rm eff}} \mathrm{d}E'\, q(E'), \quad \textbf{where} \quad t = \int_{E}^{E_{\rm eff}} \frac{\mathrm{d}E'}{\dot{E}'}$$

$$\dot{E} = \dot{E}_{\rm syn} + \dot{E}_{\rm ic} + \dot{E}_{\rm ad} + etc / \dot{E}_{\rm syn} + \dot{E}_{\rm pp} + \dot{E}_{\rm p\gamma} + etc$$

Fast Cooling *(Saturation)*

$$E_{\rm eff} \to \infty$$

$$f(E) = \frac{1}{\dot{E}} \int_{E}^{\infty} \mathrm{d}E'\, q(E')$$

Slow Cooling

$$t \ll E/\dot{E}$$

$$f(E,t) = q(E) \cdot t$$

Some Remarks

Used simplifications

- Acceleration and Losses are treated independently
  - High energy cut-off depends on loss rate
  - Some acceleration processes cannot be treated in this way, e.g. *converter mechanism by Derishev*
- Particles lose energy by small fractions, which is not true for some processes, e.g. IC in the Klein-Nishina regime

Transport Equation with Diffusion and Escape

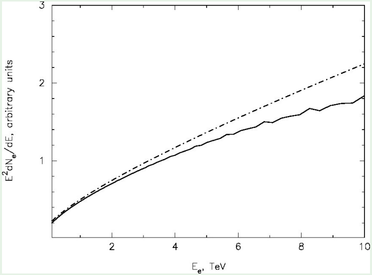
$$\frac{\partial f}{\partial t} + \frac{\partial(\dot{E} f)}{\partial E} + \nabla\left(D \nabla f\right) + \frac{f}{\tau} = q(E, t)$$

also can be solved analytically, see e.g. Ginzburg's "Astrophysics of Cosmic Rays"

Some Remarks

Klein-Nishina and Continues Loss approximation

- Particles lose energy by small fractions, which is not true for some processes, e.g. IC in the Klein-Nishina regime



Solid line: $c\sigma_{\rm ic}f(\gamma) = q(\gamma) + c\int\limits_{\gamma}^{\infty} {\rm d}\gamma' f(\gamma')\frac{{\rm d}\sigma}{{\rm d}E_\gamma}(\gamma',\gamma'-\gamma)$

Dash-dotted line: $f(\gamma) = \frac{1}{\dot{E}_{\rm ic}}\int\limits_{\gamma}^{\infty}{\rm d}\gamma' q(\gamma')$

Some Remarks

High Acceleration Cut-Off

- Acceleration Time

$$t_{\mathrm{acc}} = 0.1\eta E_{\mathrm{TeV}} B_{\mathrm{G}}^{-1}\,\mathrm{s}\,(\text{where}\,\eta > 1)$$

- Cooling Time

$$t_{\mathrm{cool}} = E/\dot{E}$$

$$t_{\mathrm{acc}} < t_{\mathrm{cool}}$$

- Dominant Synchrotron Losses

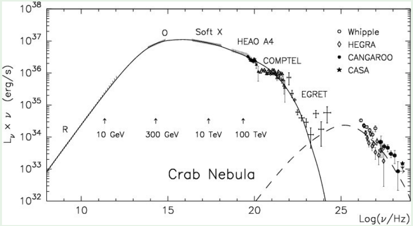
$$\gamma < 10^8 B_{\mathrm{G}}^{-1/2}\eta^{-1/2}$$

$$\hbar\omega < 100\eta^{-1}\mathrm{MeV}$$

An Extreme Accelerator?

Crab Nebula

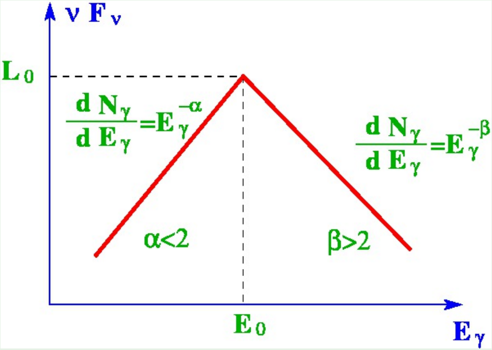
Broad Band Spectrum



νF_ν peak gives the luminosity

νF_ν peaking distribution

$$\nu F_\nu = E_\gamma^2 \frac{\mathrm{d}N_\gamma}{\mathrm{d}E_\gamma}$$



$$L_\gamma = \int \mathrm{d}E_\gamma\, E_\gamma \frac{\mathrm{d}N_\gamma}{\mathrm{d}E_\gamma} =$$

$$\int_{E_{\min}}^{E_0} \mathrm{d}E_\gamma\, E_\gamma^{1-\alpha} + \int_{E_0}^{E_{\max}} \mathrm{d}E_\gamma\, E_\gamma^{1-\beta}$$

$$E_{\min} \ll E_0 \ll E_{\max}$$

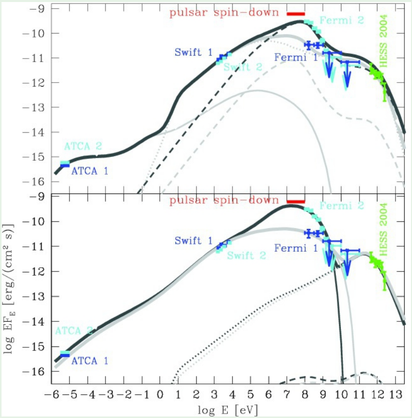
$$L_\gamma = L_0 \left(\frac{1}{2-\alpha} + \frac{1}{\beta-2} \right)$$

For $\alpha = 1.5$ and $\beta = 2.5$

$$L_\gamma = 4 L_0$$

νF_ν peak gives order of magnitude estimate of the luminosity

Fermi/LAT observations of PSR B1259-63



Detailed information about the pulsar spin-down luminosity provides very precise information about the available energetics

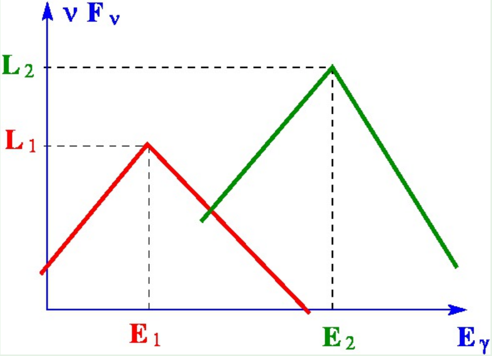
$$L_{\rm SD} = 8.3\times 10^{35} {\rm erg\,s^{-1}}$$

$$L_{\rm LAT} = 8\times 10^{35}\left(\frac{D}{2.3{\rm kpc}}\right)^2 {\rm erg\,s^{-1}}$$

Even in this case, there are unavoidable uncertainties related to the distance to the source...

Radiation Production

Emission of a Particle (two channels)



Single particle spectra:

$$\frac{\mathrm{d}N_i}{\mathrm{d}E_\gamma} = K_i\left(E_\gamma, E_0\right)$$

Total luminosity:

$$L = \dot{E}_1 + \dot{E}_2$$

Luminosity per channel:

$$L_i = \frac{\dot{E}_i}{\dot{E}_1 + \dot{E}_2} L$$

Ratio of the humps:

$$\frac{L_1}{L_2} = \frac{\dot{E}_1}{\dot{E}_2}$$

Comparison of Radiation Mechanisms

Radiation Efficiency

- Escape Time: $t_{\rm esc} = \min(t_{\rm diff}, t_{\rm ad})$

$$t_{\rm diff} = \frac{R^2}{2D} \sim 2 \cdot 10^4 \, \zeta^{-1} R_{12}^2 B_1 E_1^{-1} \, \mathrm{s}, \quad \zeta = \frac{D}{D_{\rm Bohm}}$$

$$t_{\rm ad} = \frac{R}{V_{\rm bulk}} \sim 10^2 \, R_{12} V_{10}^{-1} \, \mathrm{s}$$

- Energy Transfer: $\mu = \frac{E_\gamma}{E_0}$
- Radiation Efficiency: $\kappa = \mu \min(1, t_{\rm esc}/t_{\rm int})$

Radiation Mechanism in BS

Inverse Compton Scattering

- Cooling Time:

$$t_{\rm ic} = 40\left(\frac{L}{10^{38}{\rm erg/s}}\right)^{-1}\left(\frac{R}{10^{12}{\rm cm}}\right)^{2}\left(\frac{T}{3\cdot 10^{4}{\rm K}}\right)^{1.7} E_{\rm TeV}^{0.7}\ {\rm s}$$

- Energy Transfer:

$$E_\gamma = \begin{cases} E_{\rm e}, & \epsilon E \gg m^2c^4 \\ \frac{\epsilon E_{\rm e}^2}{m^2c^4}, & \epsilon E \ll m^2c^4 \end{cases}$$

- Radiation Efficiency

$$\kappa \sim 1$$

Radiation Mechanism in BS

Proton-proton interaction

- Cooling Time:

$$t_{\rm pp} = 10^6 \left(\frac{n_{\rm p}}{10^9{\rm cm}^{-3}}\right)^{-1} {\rm s}$$

- Energy Transfer:

$$E_\gamma \sim 0.1\, E_{\rm p}$$

- Radiation Efficiency

$$\kappa = 10^{-3} \frac{t_{\rm esc}}{10^4{\rm s}} \frac{n_{\rm p}}{10^9{\rm cm}^{-3}}$$

Radiation Mechanism in BS

Photo-meson production

- Cooling Time:

$$t_{\mathrm{p}\gamma} = 3 \cdot 10^4 \left(\frac{L}{10^{38}\mathrm{erg/s}}\right)^{-1} \left(\frac{R}{10^{12}\mathrm{cm}}\right)^{2} \left(\frac{T}{3 \cdot 10^4\mathrm{K}}\right) \mathrm{s}$$

- Energy Transfer:

$$E_\gamma \sim 0.1\, E_\mathrm{p}$$

- Radiation Efficiency

$$\kappa = 0.03 \frac{t_{\mathrm{esc}}}{10^4\mathrm{s}} \frac{L}{10^{38}\mathrm{erg/s}} \left(\frac{R}{10^{12}\mathrm{cm}}\right)^{-2} \left(\frac{T}{3 \cdot 10^4\mathrm{K}}\right)^{-1}$$

Radiation Mechanism in BS

Photo-disintegration (see Bosch-Ramon&Khangulyan, 2009)

- Cooling Time:

$$t_{\rm pd} \sim 3\cdot 10^3 \left(\frac{L}{10^{38}{\rm erg/s}}\right)^{-1} \left(\frac{T}{3\cdot 10^4{\rm K}}\right) \left(\frac{R}{10^{12}{\rm cm}}\right)^{2} {\rm s}$$

- Energy Transfer:

$$E_\gamma \sim 0.01\, E_{\rm N}$$

- Radiation Efficiency

$$\kappa = 0.03 \frac{t_{\rm esc}}{10^4{\rm s}} \frac{L}{10^{38}{\rm erg/s}} \left(\frac{R}{10^{12}{\rm cm}}\right)^{-2} \left(\frac{T}{3\cdot 10^4{\rm K}}\right)^{-1}$$

The most Favorable Emission Process in BS

Radiation Processes

Proc.	E_γ/E_0	κ
IC	1	1
pp	0.1	$10^{-3}\,\frac{t_{\rm esc}}{10^4\,{\rm s}}\,\frac{n_{\rm p}}{10^9\,{\rm cm}^{-3}}$
pγ	0.1	$0.03\,\frac{t_{\rm esc}}{10^4\,{\rm s}}\,\frac{L}{10^{38}\,{\rm erg/s}}\left(\frac{R}{10^{12}\,{\rm cm}}\right)^{-2}\left(\frac{T}{3\cdot10^4\,{\rm K}}\right)^{-1}$
Photo-des.	0.01	$0.03\,\frac{t_{\rm esc}}{10^4\,{\rm s}}\,\frac{L}{10^{38}\,{\rm erg/s}}\left(\frac{R}{10^{12}\,{\rm cm}}\right)^{-2}\left(\frac{T}{3\cdot10^4\,{\rm K}}\right)^{-1}$

Proton Synchrotron

Electrons

- Cooling: $t_{\rm cool} = 400 E_{\rm TeV}^{-1} B_{\rm G}^{-2}\ {\rm s}$
- Photon Energy: $\hbar\omega = 20 E_{\rm TeV}^{2} B_{\rm G}\ {\rm keV}$
- Highest Energy Cooling: $t_{\rm cool} = 6\eta^{1/2} B_{\rm G}^{-3/2}\ {\rm s}$
- Highest Energy Photons: $\hbar\omega = 100\eta^{-1}\ {\rm MeV}$

Protons

- Cooling: $t_{\rm cool} = 400 E_{\rm TeV}^{-1} B_{\rm G}^{-2} \left(\frac{m_{\rm p}}{m_{\rm e}}\right)^4\ {\rm s}$
- Photon Energy: $\hbar\omega = 20 E_{\rm TeV}^{2} B_{\rm G} \left(\frac{m_{\rm e}}{m_{\rm p}}\right)^3\ {\rm keV}$
- Highest Energy Cooling: $t_{\rm cool} = 6\eta^{1/2} B_{\rm G}^{-3/2} \left(\frac{m_{\rm p}}{m_{\rm e}}\right)^2\ {\rm s}$
- Highest Energy Photons: $\hbar\omega = 100\eta^{-1} \left(\frac{m_{\rm p}}{m_{\rm e}}\right)\ {\rm MeV}$

Synchrotron-IC Model

Very similar processes

- Energy Losses

$$\dot{E}_{\rm IC} = -\frac{4}{3} U_{\rm ph} c \gamma^2 \qquad \dot{E}_{\rm syn} = -\frac{4}{3} U_{\rm B} c \gamma^2$$

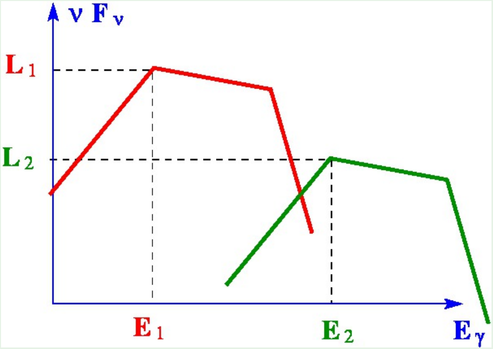
- Mean Energy

$$\hbar\omega = \left(\frac{4}{3}\hbar\omega_0\right)\gamma^2 \qquad \hbar\omega = \left(\frac{eB\hbar}{2\pi m_{\rm e} c}\right)\gamma^2$$

$$\frac{L_{\rm syn}}{L_{\rm ic}} = \frac{U_{\rm B}}{U_{\rm ph}} \qquad \frac{\hbar\omega_{\rm syn}}{\hbar\omega_{\rm ic}} = \frac{\left(\frac{eB\hbar}{2\pi m_{\rm e} c}\right)}{\left(\frac{4}{3}\hbar\omega_0\right)}$$

Synchrotron-IC Model

Two identical humps?



Ratio of the peaks

$$\frac{L_{\rm syn}}{L_{\rm ic}} = \frac{U_{\rm B}}{U_{\rm ph}}$$

Ratio of the energies

$$\frac{\hbar\omega_{\rm syn}}{\hbar\omega_{\rm ic}} = \frac{\left(\frac{eB\hbar}{2\pi m_e c}\right)}{\left(\frac{4}{3}\hbar\omega_0\right)}$$

Kein-Nishina Cut-off

Photon Energy < Electron Energy

$$\hbar\omega = \left(\frac{4}{3}\hbar\omega_0\right)\gamma^2 < \gamma m_e c^2$$

$$\gamma < \left(\frac{m_e c^2}{\frac{4}{3}\hbar\omega_0}\right)$$

$$\gamma < 5 \times 10^5 \omega_{0,\mathrm{eV}}^{-1}$$

$$\hbar\omega = \left(\frac{eB\hbar}{2\pi m_e c}\right)\gamma^2 < \gamma m_e c^2$$

$$\gamma < \left(\frac{2\pi m_e^2 c^3}{eB\hbar}\right)$$

$$\gamma < 3 \times 10^{14} B_{\mathrm{G}}^{-1}$$

Some Remarks

High Acceleration Cut-Off

- Acceleration Time

$$t_{acc} = 0.1\eta E_{\mathrm{TeV}} B_{\mathrm{G}}^{-1}\,\mathrm{s}\;(\text{where}\;\eta > 1)$$

- Cooling Time

$$t_{cool} = E/\dot{E}$$

$$t_{acc} < t_{cool}$$

- Dominant Synchrotron Losses

$$\gamma < 10^8 B_{\mathrm{G}}^{-1/2}\eta^{-1/2}$$

$$\hbar\omega < 100\eta^{-1}\mathrm{MeV}$$

Kein-Nishina Cut-off

Photon Energy < Electron Energy

$$\hbar\omega = \left(\frac{4}{3}\hbar\omega_0\right)\gamma^2 < \gamma m_e c^2$$

$$\gamma < \left(\frac{m_e c^2}{\frac{4}{3}\hbar\omega_0}\right)$$

$$\gamma < 5 \times 10^5 \omega_{0,\mathrm{eV}}^{-1}$$

$$\hbar\omega = \left(\frac{eB\hbar}{2\pi m_e c}\right)\gamma^2 < \gamma m_e c^2$$

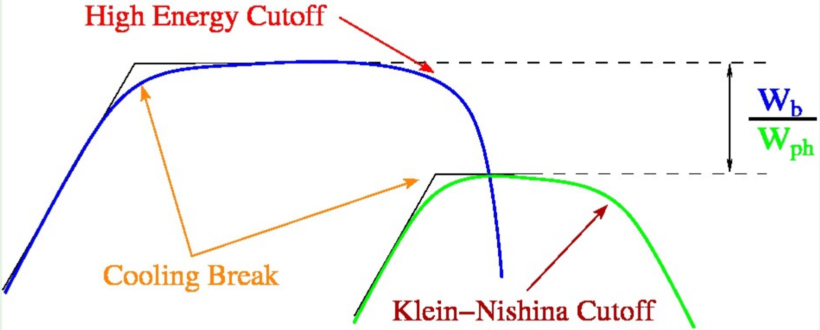
$$\gamma < \left(\frac{2\pi m_e^2 c^3}{eB\hbar}\right)$$

$$\gamma < 3 \times 10^{14} B_{\mathrm{G}}^{-1}$$

$$B_{\mathrm{G}} > 10^{12}\eta$$

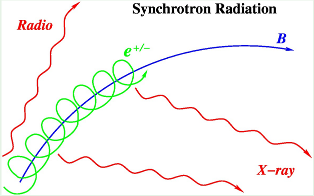
Leptonic Radiation Mechanisms

Typical SED



Synchrotron Radiation

Electrons can interact with B-field



- Energy Losses: $\dot{E}_{\rm syn} = -\frac{4}{3} U_{\rm B} c\gamma^2$
- Mean Energy: $\hbar\omega = \left(\frac{eB\hbar}{2\pi m_{\rm e} c}\right)\gamma^2$
- Single Particle Spectrum:

$$\frac{{\rm d}I_{\rm syn}}{{\rm d}\omega} = \frac{\sqrt{3}}{2\pi}\frac{e^3 B}{mc^2} F\left(\frac{\omega}{\omega_{\rm c}}\right)$$

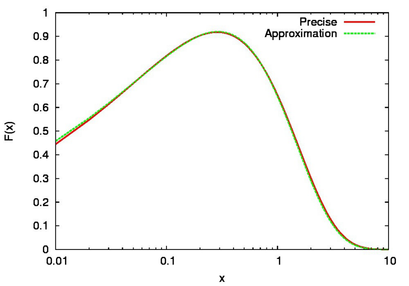
where $\omega_{\rm c} = \frac{3eB\gamma^2}{2mc}$

- Useful approximation:

$$F(x) = x\int_x^\infty K_{5/3}(x'){\rm d}x' = 1.76\,x^{0.29}{\rm e}^{-x}$$

Synchrotron Radiation

Approximation for the peak



- $x \gg 1$

$$F(x) = \left(\frac{\pi}{2}\right)^{1/2} x^{1/2} \mathrm{e}^{-x}$$

- $x \ll 1$

$$F(x) = \frac{4\pi}{\sqrt{3}\Gamma(1/3)} x^{1/3}$$

- Useful approximation (but not an asymptotic):

$$F(x) = x \int_x^\infty K_{5/3}(x')\mathrm{d}x' = 1.76\, x^{0.29} \mathrm{e}^{-x}$$

Inverse Compton Radiation

Electrons can interact with photon field

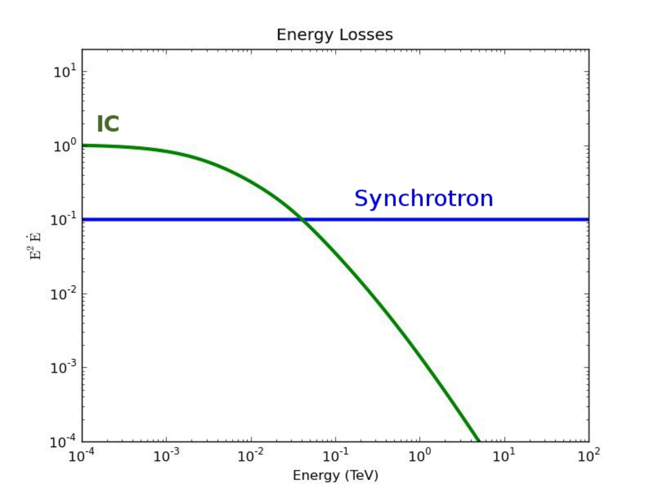
- Maximum Energy of Gamma Rays $E_\gamma < \frac{\gamma\left(1-\frac{1}{4\gamma^2}\right)}{1+\frac{1}{4\gamma\epsilon}}$
- Single Particle Spectrum:

$$\frac{\mathrm{d}\sigma_\gamma}{\mathrm{d}E_\gamma} = \frac{\pi r_e^2 \epsilon^2 E_\gamma}{\gamma^3(\gamma - E_\gamma)}\left[\ln\frac{E_\gamma}{\gamma\epsilon(\gamma - E_\gamma)} + (4\epsilon\gamma^2 - 4\gamma\epsilon E_\gamma - E_\gamma)\frac{(2\epsilon\gamma^2 - 2\gamma\epsilon E_\gamma + \epsilon E_\gamma^2 + E_\gamma)}{4E_\gamma\gamma\epsilon(\gamma - E_\gamma)}\right]$$

- Energy Losses for a Planckian photon field:

$$\dot{\gamma}_{IC} = 5.5\times10^{17}\, T_{\mathrm{mcc}}^3\gamma\frac{ln(1+0.55\gamma T_{\mathrm{mcc}})}{1+25T_{\mathrm{mcc}}\gamma}\left(1+\frac{1.4\gamma T_{\mathrm{mcc}}}{1+12\gamma^2T_{\mathrm{mcc}}^2}\right)\ \mathrm{s}^{-1},$$

Klein-Nishina Effect



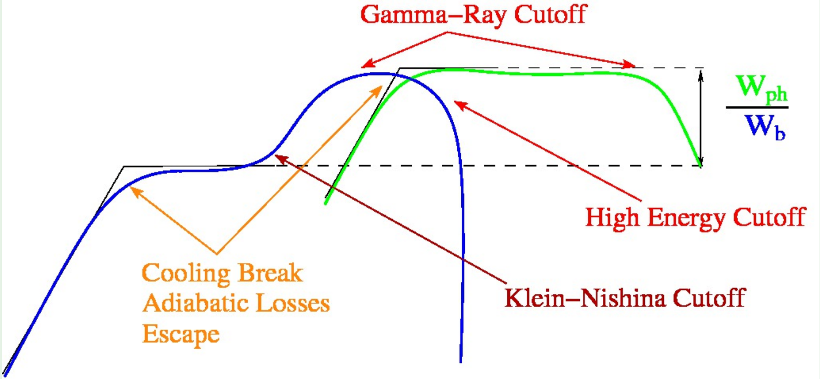
Klein-Nishina Effect

$$\frac{\mathrm{d}N_\mathrm{e}}{\mathrm{d}E} = \frac{1}{\dot{E}} \int_E^\infty \mathrm{d}E' \, Q(E) \qquad \dot{E} = \dot{E}_\mathrm{syn} + \dot{E}_\mathrm{ic}$$

Klein-Nishina Effect

- X-ray: hardening
- γ-rays: no Klein-Nishina cutoff

Klein-Nishina Effect



Compton Scattering Spectrum

$$\frac{dN_\gamma}{dE_\gamma} = \int dE_e c(1 - \cos\theta) n_{ph} \frac{dN_e}{dE_e} \frac{d\sigma}{dE_\gamma}$$

$$\frac{d^2N(\theta,\omega)}{d\omega\, d\Omega} = \frac{r_0^2}{2\omega_0 E^2}\left[1 + \frac{\omega^2}{2E(E-\omega)} - \frac{\omega}{\omega_0 E(E-\omega)(1-\cos\theta)} + \frac{\omega^2}{2\omega_0^2 E^2 (E-\omega)^2 (1-\cos\theta)^2}\right]$$

$$\equiv \frac{r_0^2}{2\omega_0 E^2}\left[1 + \frac{z^2}{2(1-z)} - \frac{2z}{b_\theta(1-z)} + \frac{2z^2}{b_\theta^2(1-z)^2}\right],$$

where $b_\theta \equiv 2(1-\cos\theta)\omega_0 E$, $z \equiv \omega/E$, and ω changes in the limits

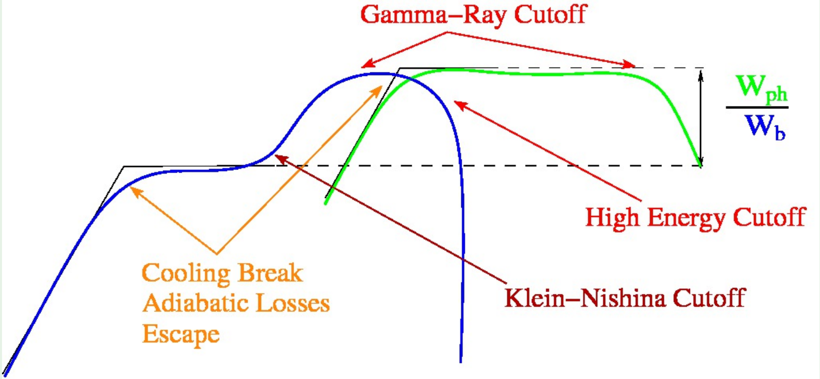
$$\omega_0 \ll \omega \leqslant \frac{b_\theta}{1+b_\theta} E.$$

Aharonian&Atoyan, 1981

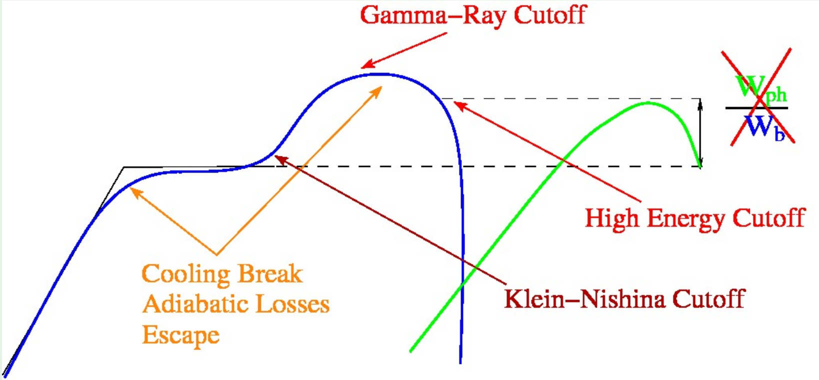
$$\frac{\mathrm{d}N_\gamma}{\mathrm{d}E_\gamma} = \int \mathrm{d}E_\mathrm{e} c(1 - \cos\theta) n_\mathrm{ph} \frac{\mathrm{d}N_\mathrm{e}}{\mathrm{d}E_\mathrm{e}} \frac{\mathrm{d}\sigma}{\mathrm{d}E_\gamma}$$

Anisotropic inverse Compton

Klein-Nishina Effect



Klein-Nishina + Anisotropic IC

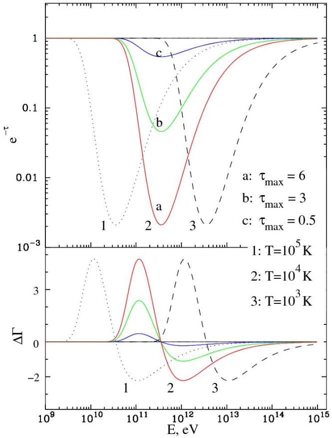


Gamma-Gamma Absorption

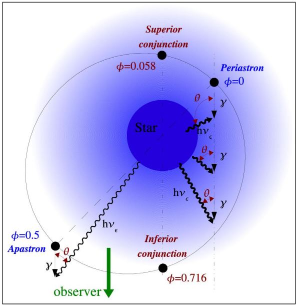
- The KN regime implies importance of γ-γ absorption

$$\gamma\epsilon > 1$$

- Does KN imply strong attenuation?
- Does strong attenuation implies EMC?



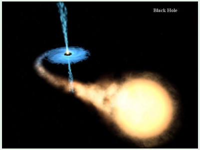
LS 5039



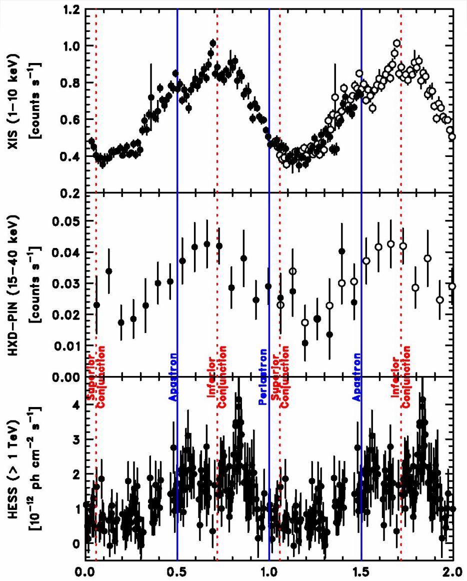
From Aharonian et al., 2006
A general study of γ- and X-rays production in the leptonic scenario

Binary Pulsar

Microquasar



X-ray and TeV emission from LS5039



- Variable/Periodic
- Apparent similarities in lightcurves
- Hard distributions of parent particles

Takahashi et al., 2009

X-ray and TeV emission from LS5039

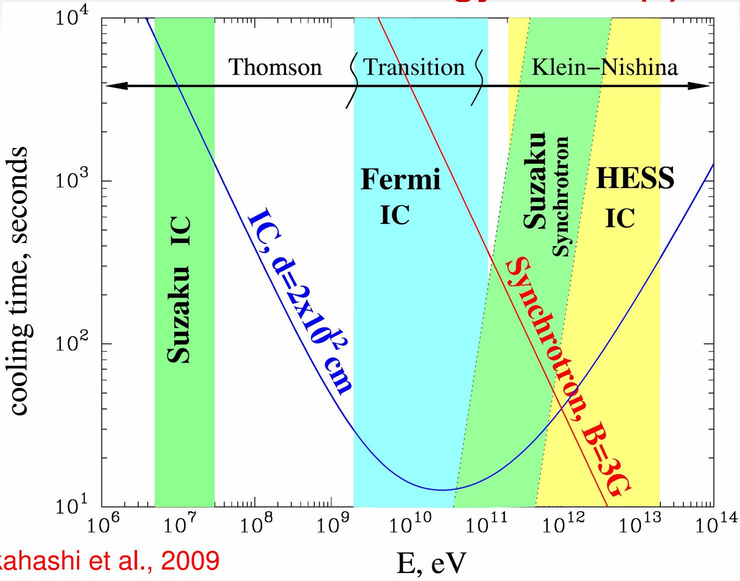
TeV (Aharonian et al., 2006)

- Variable
- Periodic
- Strong variability in flux level
- Significant variability in photon index
- SUPC: lower fluxes and steeper spectra
- INFC: higher fluxes and harder spectra
- Very hard spectra at INFC

X-ray (Takahashi et al., 2009)

- Variable
- Seems to be periodic
- Significant variability in flux level
- Minor variability in photon index
- SUPC: lower fluxes and steeper spectra
- INFC: higher fluxes and harder spectra
- Hard spectra

Time-scales and Energy Bands (II)



Takahashi et al., 2009

Modeling (results)

- Adiabatic cooling rate from X-ray data
- Good agreement with HESS fluxes
- Acceptable agreement with HESS spectral indexes
- Testable prediction for Fermi