Leptonic radiative processes in the context of gamma-ray binary systems

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Variable Galactic Gamma-Ray Sources
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Outline

1. Introduction
    - Leptonic production mechanisms
    - Leptons vs Hadrons
2. Leptonic Radiation Mechanisms in BS
    - Klein-Nishina Effect
    - Anisotropic inverse Compton
    - Multiwavelength Properties
3. Summary
    - Summary

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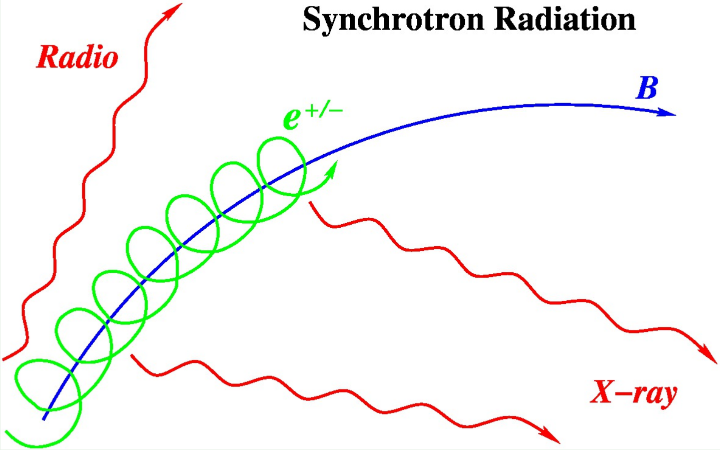
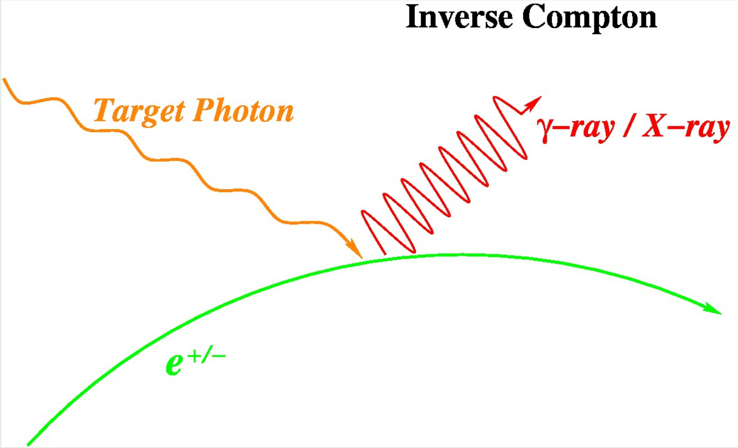
Leptonic Radiation Mechanisms

Electrons can interact with B-field



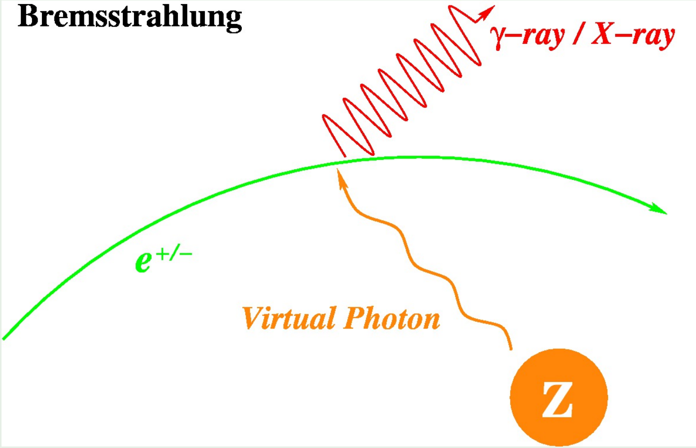
Leptonic Radiation Mechanisms

Electrons can interact with photon field



Leptonic Radiation Mechanisms

Electrons can interact with matter



Leptonic Radiation Mechanisms

Energy Losses

$t_{\rm syn} = 400 E_{\rm TeV}^{-1} B_{\rm G}^{-2}\,{\rm s}$ $t_{\rm ic} = 16 E_{\rm TeV}^{-1} w_{\rm erg/cm^3}^{-1}\,{\rm s}$ $t_{\rm br} = 10^5 n_{10}^{-1}\,{\rm s}$

Magnetic field (G)

$B_{\rm co} = 10\sigma^{1/2} L_{36} R_{12}^{-2}$ $B_{\rm surf} \sim 200 - 10^3$

Photon field $({\rm erg\,cm^{-3}})$

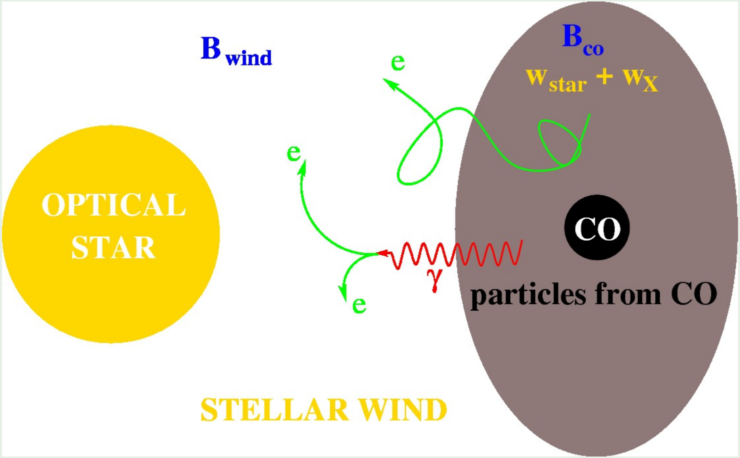
$w_{\rm X} = 2.5 \times 10^2 L_{{\rm X},38} R_{12}^{-2}$ $w_{\rm ph} = 2.5 \times 10^2 L_{*,38} R_{12}^{-2}$

Matter density $({\rm cm^{-3}})$

$n_{\rm jet} = 10^5 \theta_{-1}^{-2} R_{12}^{-2} L_{36}$ $n_{\rm wind} \sim 3 \times 10^8 M_{-8} R_{12}^{-2}$

VHE Leptons

Physical regions in BS



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Leptonic Radiation Mechanisms

$$\frac{\mathrm{d}N_{\mathrm{e}}}{\mathrm{d}t\mathrm{d}E} \propto E^{-\alpha_{\mathrm{i}}} \qquad \frac{\mathrm{d}N_{\mathrm{e}}}{\mathrm{d}E} \propto E^{-\alpha_{\mathrm{e}}} \qquad \frac{\mathrm{d}N_{\mathrm{ph}}}{\mathrm{d}t\mathrm{d}E} \propto E^{-\alpha_{\mathrm{ph}}}$$

Energy Losses

$t_{\mathrm{syn}} = 400 E_{\mathrm{TeV}}^{-1} B_{\mathrm{G}}^{-2}\mathrm{s}$ $t_{\mathrm{ic}} = 16 E_{\mathrm{TeV}}^{-1} w_{\mathrm{erg/cm^3}}^{-1}\,\mathrm{s}$ Br-Es-Ad

Electron Spectrum Modification

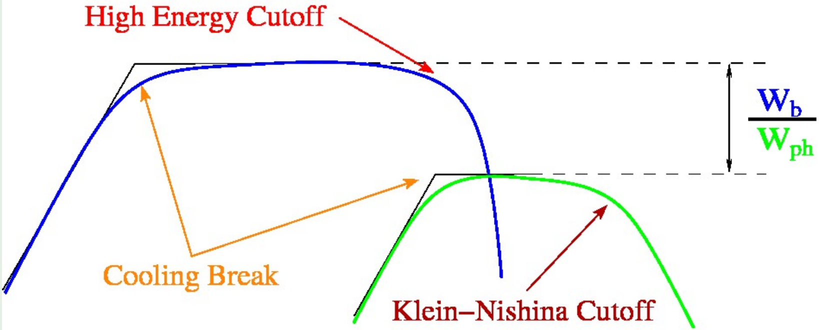
$\alpha_{\mathrm{e}} = \alpha_{\mathrm{i}} + 1$ $\alpha_{\mathrm{e}} = \alpha_{\mathrm{i}} + 1$ $\alpha_{\mathrm{e}} = \alpha_{\mathrm{i}}$

Radiation Spectrum

$\alpha_{\mathrm{ph}} = \frac{\alpha_{\mathrm{e}} + 1}{2}$ $\alpha_{\mathrm{ph}} = \frac{\alpha_{\mathrm{e}} + 1}{2}$ $\alpha_{\mathrm{ph}} = \alpha_{\mathrm{e}}$

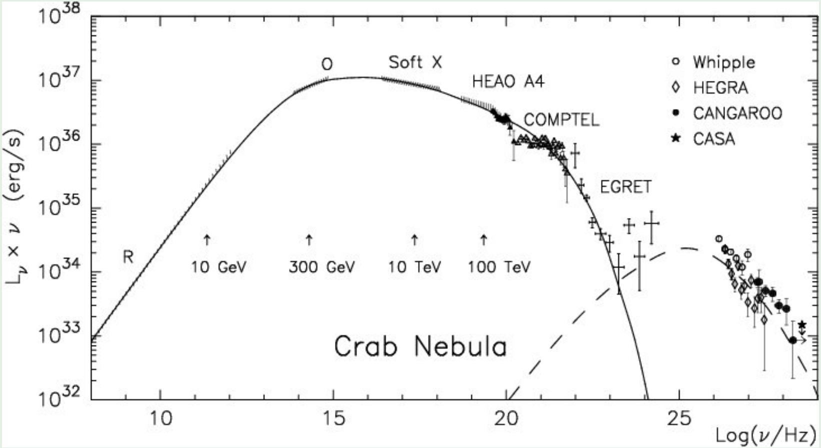
Leptonic Radiation Mechanisms

Typical SED



Leptonic Radiation Mechanisms

Crab Nebula (Aharonian&Atoyan)



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Radiation Mechanism in BS

Radiation Efficiency

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

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

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

- 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:

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

- Radiation Efficiency

$$\kappa \sim 1$$

Radiation Mechanism in BS

Proton-proton interaction

- Cooling Time:

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

- Energy Transfer:

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

- Radiation Efficiency

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

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, 2008)

- 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	$0.03\,\frac{t_{\rm esc}}{10^4\,{\rm s}}\,\frac{L}{10^{38}\,{\rm erg/s}}\left(\frac{R}{10^{12}\,{\rm cm}}\right)^{-2}\left(\frac{T}{3\cdot 10^4\,{\rm K}}\right)^{-1}$
Photo-des.	0.01	$0.03\,\frac{t_{\rm esc}}{10^4\,{\rm s}}\,\frac{L}{10^{38}\,{\rm erg/s}}\left(\frac{R}{10^{12}\,{\rm cm}}\right)^{-2}\left(\frac{T}{3\cdot 10^4\,{\rm K}}\right)^{-1}$

IC as a Primary Emission Mechanism

- Optical Star Photon Field is perfect Target
    - All over the System
    - Fast cooling
- “Small” energy of parent Leptons $E_\gamma \sim E_{\rm e}$
    - Easier to accelerate
    - Easier to confine

Acceleration vs Losses

Acceleration time

$$t_{\rm acc} \approx 10\eta_{10} E_{\rm TeV} B_{0.1}^{-1}$$

Hillas Criterion

$$E < 3 \cdot 10 \left(\frac{R_{\rm acc}}{10^{12}}\right) B_{0.1}\ {\rm TeV}$$

Klein-Nishina losses

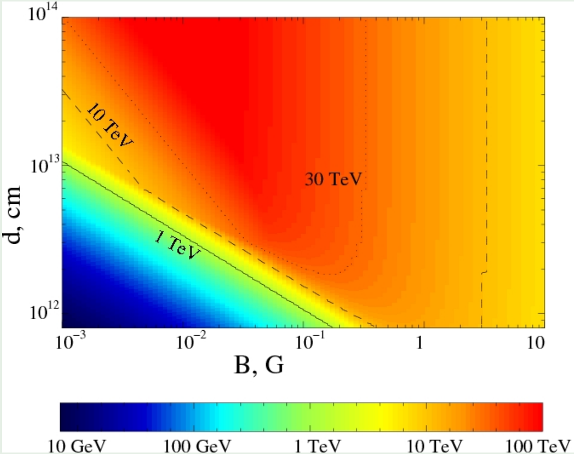
$$t_{\rm cool} \approx 2 \cdot 10^2 w_0^{-1} E_{\rm TeV}^{0.7}\ {\rm s} \qquad E < 8 \cdot 10^3 \left[B_{0.1}\eta_{10}^{-1} w_0^{-1}\right]^{3.3}\ {\rm TeV}$$

Synchrotron losses

$$t_{\rm cool} \approx 4 \cdot 10^4 B_{0.1}^{-2} E_{\rm TeV}^{-1}\ {\rm s} \qquad E < 6 \cdot 10\, B_{0.1}^{-1/2}\, \eta_{10}^{-1/2}\ {\rm TeV}$$

Electron maximum energy in LS 5039

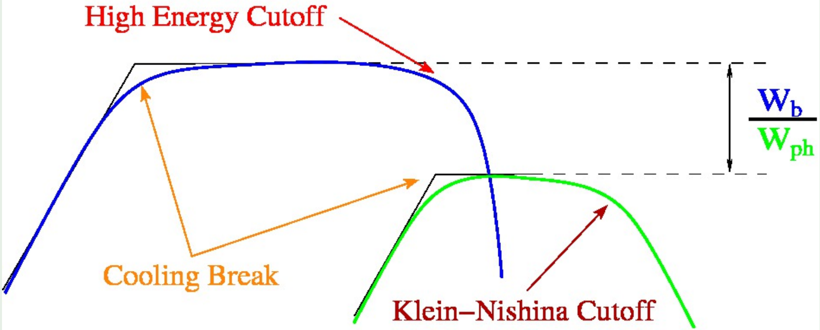
Max.Energy vs B-field and distance to the star



Outline

Leptonic Radiation Mechanisms

Typical SED



Electron Energy Distribution

Steady electron distribution

$$\frac{\mathrm{d}N_{\mathrm{e}}}{\mathrm{d}E} = \frac{1}{\dot{E}} \int_{E}^{\infty} \mathrm{d}E' \, Q(E)$$

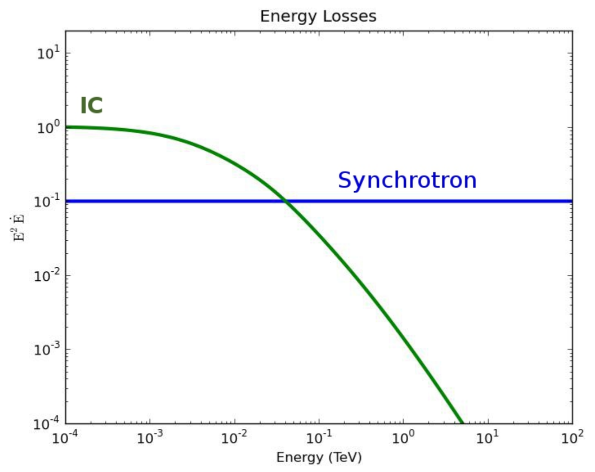
$$\dot{E} = \dot{E}_{\mathrm{syn}} + \dot{E}_{\mathrm{ic}} + \dot{E}_{\mathrm{ad}} \qquad \dot{E}_{\mathrm{syn/ad/thomson}} \propto E^{-\alpha}$$

In the case of the hot stellar photon field, the Klein-Nishina effect is important for losses:

$$\dot{\gamma}_{IC} = 5.5 \times 10^{17} T_{\mathrm{mcc}}^{3} \gamma \frac{ln(1 + 0.55\gamma T_{\mathrm{mcc}})}{1 + 25 T_{\mathrm{mcc}}\gamma} \left(1 + \frac{1.4\gamma T_{\mathrm{mcc}}}{1 + 12\gamma^{2} T_{\mathrm{mcc}}^{2}}\right) \mathrm{s}^{-1},$$

where $T_{\mathrm{mcc}} = kT/m_{\mathrm{e}}c^{2}$ (Bosch-Ramon&Khangulyan)

Klein-Nishina Effect



Klein-Nishina Effect

$$\frac{\mathrm{d}N_{\mathrm{e}}}{\mathrm{d}E} =$$

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

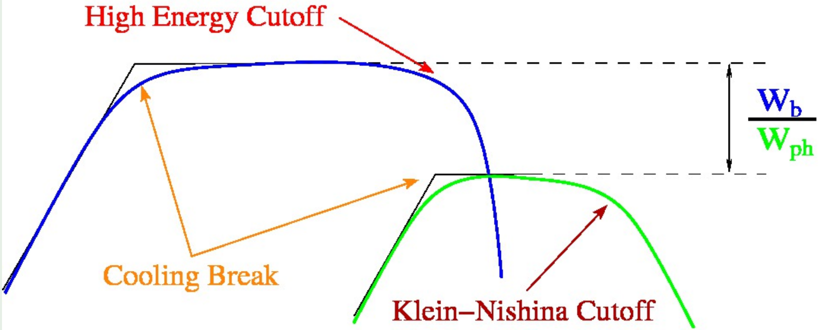
$$\dot{E} = \dot{E}_{\mathrm{syn}} + \dot{E}_{\mathrm{ic}}$$

Klein-Nishina Effect

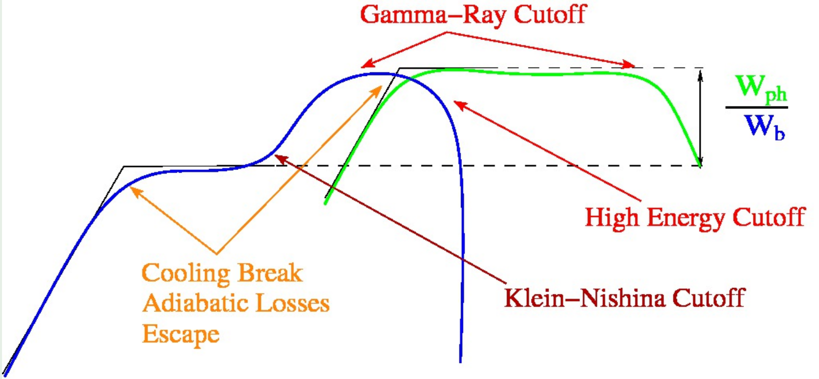
- X-ray: hardening
- γ-rays: no Klein-Nishina cutoff

Leptonic Radiation Mechanisms

Typical SED



Klein-Nishina Effect



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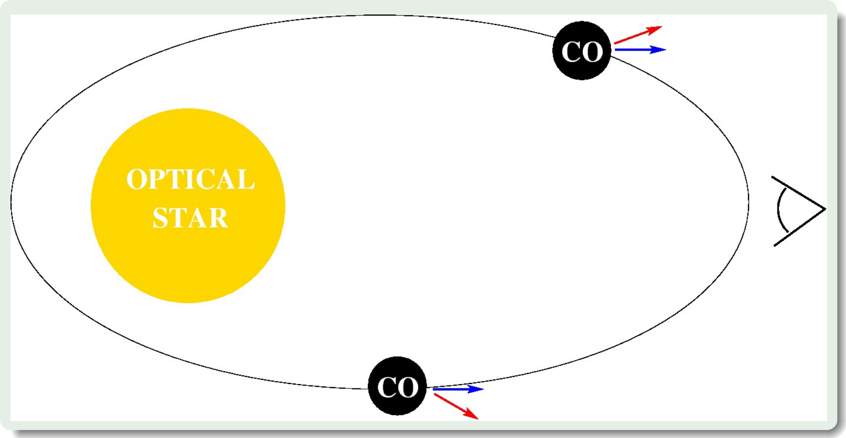
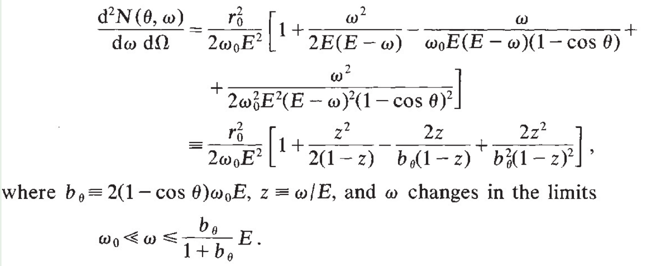
Change of the interaction angle at orbital motion



Compton Scattering Spectrum

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



$$\begin{aligned}\frac{\mathrm{d}^2 N(\theta,\omega)}{\mathrm{d}\omega\,\mathrm{d}\Omega} &= \frac{r_0^2}{2\omega_0 E^2}\left[1+\frac{\omega^2}{2E(E-\omega)}-\frac{\omega}{\omega_0 E(E-\omega)(1-\cos\theta)}+\right.\\ &\quad \left.+\frac{\omega^2}{2\omega_0^2 E^2(E-\omega)^2(1-\cos\theta)^2}\right]\\ &\equiv \frac{r_0^2}{2\omega_0 E^2}\left[1+\frac{z^2}{2(1-z)}-\frac{2z}{b_\theta(1-z)}+\frac{2z^2}{b_\theta^2(1-z)^2}\right],\end{aligned}$$

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

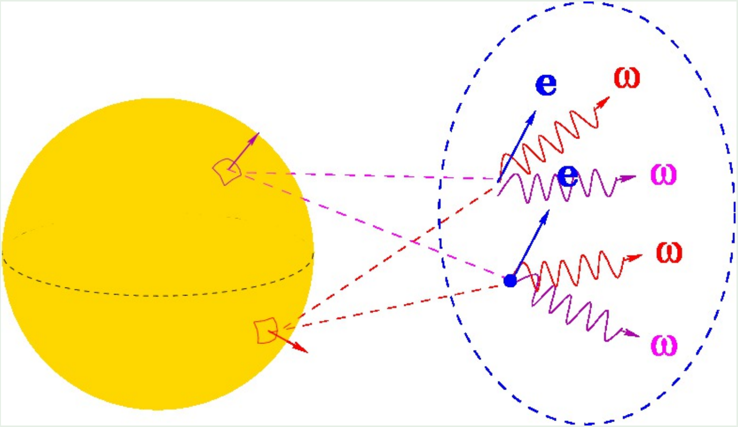
$$\omega_0 \ll \omega \leqslant \frac{b_\theta}{1+b_\theta} E .$$

Aharonian&Atoyan, 1981

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

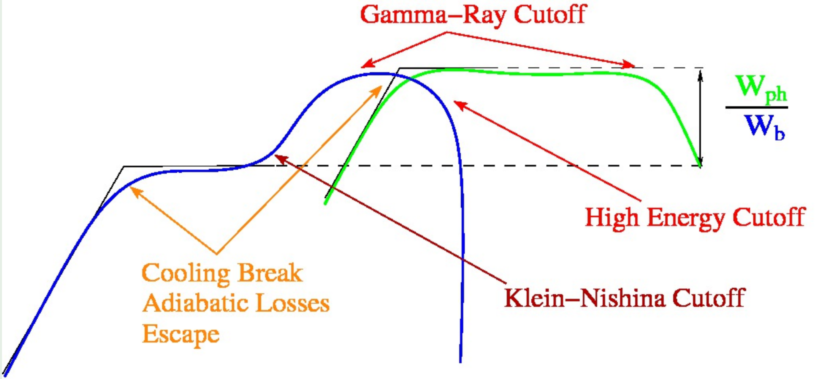
Anisotropic inverse Compton

Finite Size of the Production region / Star

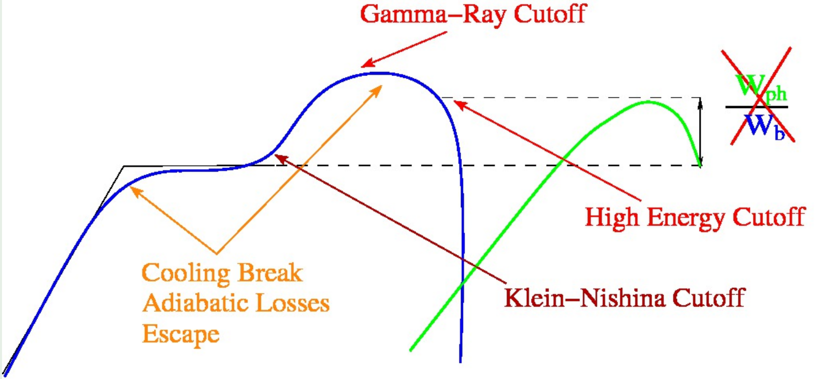


$$\frac{\mathrm{d}N_\gamma}{\mathrm{d}E_\gamma} = \int \mathrm{d}E_\mathrm{e} \int \mathrm{d}\Omega\, c(1-\cos\theta) \frac{\mathrm{d}n_\mathrm{ph}}{\mathrm{d}\Omega} \frac{\mathrm{d}N_\mathrm{e}}{\mathrm{d}E_\mathrm{e}} \frac{\mathrm{d}\sigma}{\mathrm{d}E_\gamma}$$

Klein-Nishina Effect



Klein-Nishina + Anisotropic IC



Gamma–Ray Cutoff

High Energy Cutoff

Cooling Break
Adiabatic Losses
Escape

Klein–Nishina Cutoff

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Multiwave length observations

Factors Impacting Production

	X-ray	GeV(Thomson)	TeV(Klein-Nishina)
Density	yes	yes	yes
Angle	no	yes	yes
$\gamma - \gamma$	no	no	yes

- Different combination of factors affect X-ray,GeV and TeV energy band
- i.e. Multiwavelength observations may help with determining these factors
- What are the energies of the parent particle?

Time-scales and Energy Bands

X-ray

1keV–40keV

$\sim 10^{-11}\,\mathrm{erg/cm^2s}$

Fermi

100MeV–100GeV

$\sim 5\cdot 10^{-10}\,\mathrm{erg/cm^2s}$

HESS

100GeV–100TeV

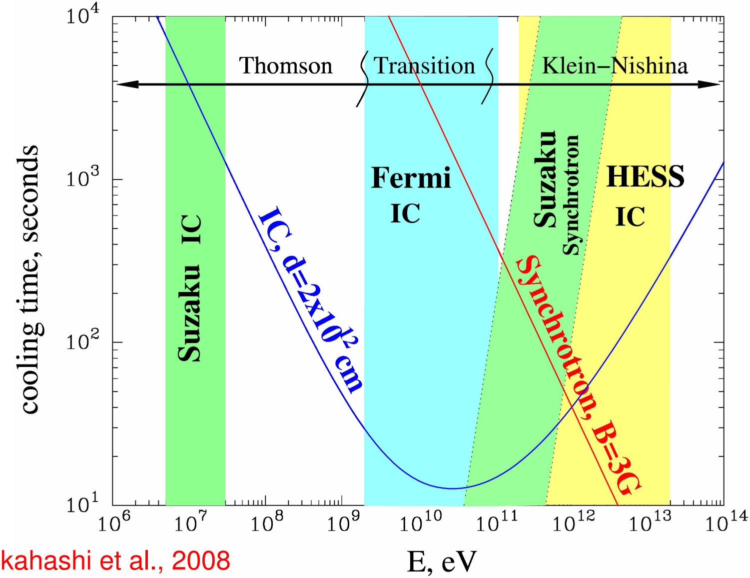
$\sim 5\cdot 10^{-11}\,\mathrm{erg/cm^2s}$

Mechanism	Energy Band	Time-scale
Synchrotron	$\hbar\omega \sim 20 E_{\rm TeV}^2 B_{\rm G}\,\mathrm{keV}$	$t_{\rm syn} \sim 4\cdot 10^2 E_{\rm TeV}^{-1} B_{\rm G}^{-2}\,\mathrm{s}$
Thomson	$\hbar\omega \sim 40 E_{\rm GeV}^2\,\mathrm{MeV}$	$t_{\rm Th} \sim 10^3 D_{13}^2 E_{\rm GeV}^{-1}\,\mathrm{s}$
Klein-Nishina	$\hbar\omega \sim E_{\rm TeV}\,\mathrm{TeV}$	$t_{\rm KN} \sim 10^3 D_{13}^2 E_{\rm TeV}^{0.7}\,\mathrm{s}$

Could be useful to consider the parent particles, i.e. to make a transformation:

(Photon Energy, Fluxes) $\Longrightarrow$ (Electron Energy, Cooling Times)

Time-scales and Energy Bands (II)



Takahashi et al., 2008

Factors Impacting Production

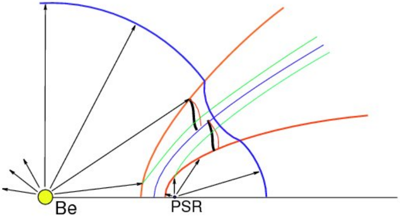
	X-ray	GeV(Thomson)	TeV(Klein-Nishina)
Density	yes	yes	yes
Angle	no	yes	yes
$\gamma - \gamma$	no	no	yes

- Angle and Attenuation are defined by the location of the production region...
- Density of the nonthermal leptons can be affected by many factors: acceleration rate, non-radiative losses, *etc*

Binary Pulsar HD model (Bogovalov et al. (2007))

Basic Assumptions

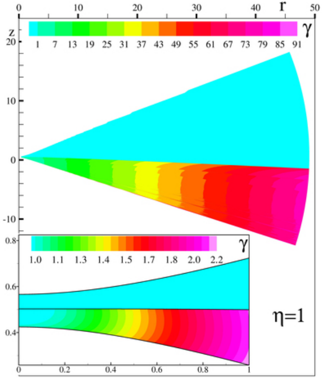
- HD
- Two radial winds
- Pulsar wind is ultrarelativistic
- Stellar wind is nonrelativistic
- Steady sate
- Two dimensional



Binary Pulsar HD Modelling

Main Results

- Very high bulk Lorentz factors, $\Gamma \sim 100$ (Bogovalov et al. 2007)
- High bulk Lorentz factors at BS scale, $\Gamma \sim 4$ (Bogovalov et al. 2007)
- Strong adiabatic losses (Khangulyan et al. 2008)
- Expected modulation of flux (in prep.)



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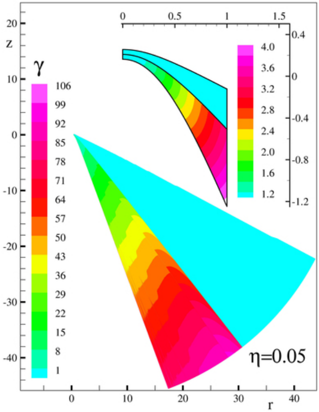

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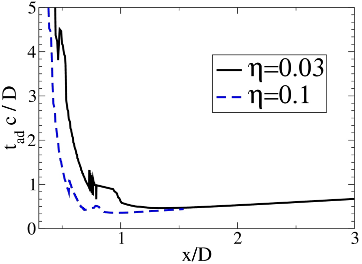

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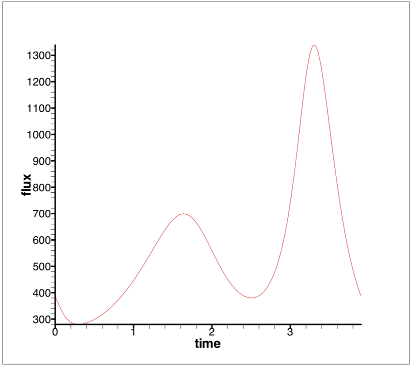
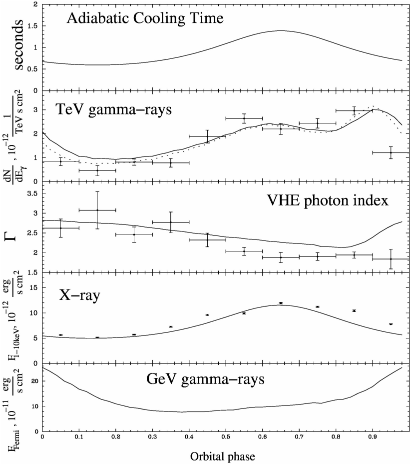


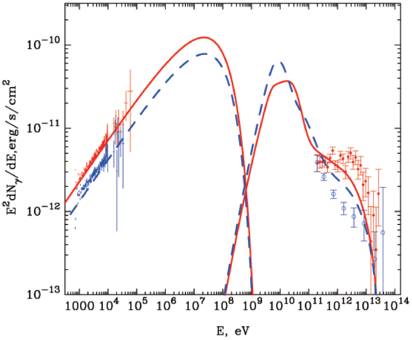
Modeling (results)

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



Modeling (results II)

- Quantitative agreement with observations
- Recalls for a detail study of possible acceleration mechanism and MHD modeling of the system



Takahashi et al, 2008

The case of LS I +61 303

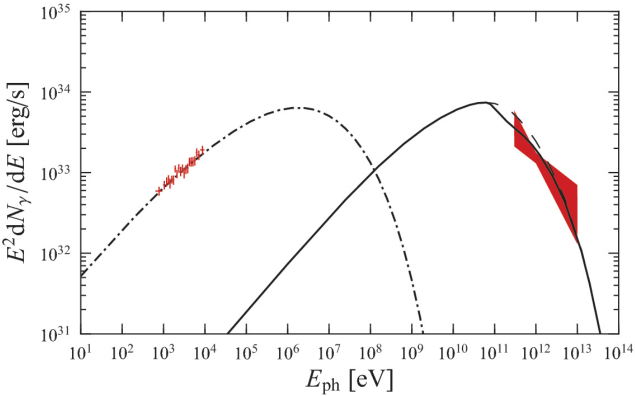


Figure: XMM-Newton and MAGIC simultaneous spectra

Zabalza et al, in press

The case of LS I +61 303

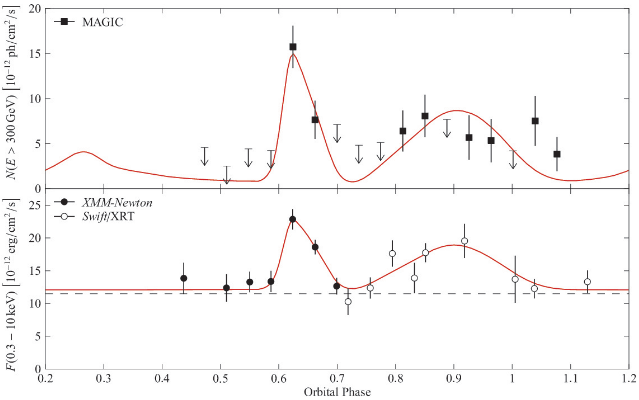
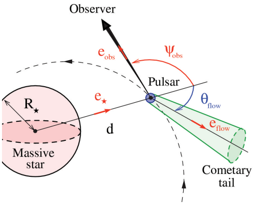
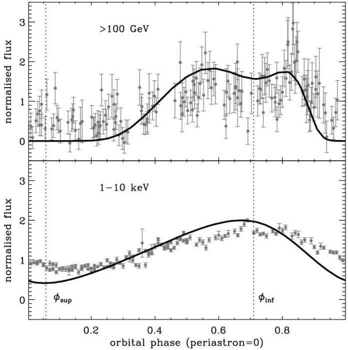


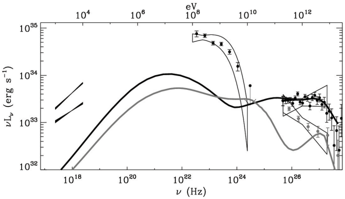
Figure: XMM-Newton and MAGIC lightcurves

Zabalza et al, in press

X- and TeV gamma-ray modeling (Doppler Boosting)







Dubus et al, 2010

Outline

1. Introduction
   - Leptonic production mechanisms
   - Leptons vs Hadrons
2. Leptonic Radiation Mechanisms in BS
   - Klein-Nishina Effect
   - Anisotropic inverse Compton
   - Multiwavelength Properties
3. Summary
   - Summary

- Binary Systems are an almost perfect leptonic source
- Given high target photon field temperature, the Klein-Nishina effect may lead to a significant change of the standard relation between the synchrotron and IC radiation components
- Anisotropic IC introduces additional modification
- HD effects are expected to be very important, although one-zone modeling allows to obtain reasonable estimates
- Different energy bands (X-ray, GeV and TeV) should behavior quite different