Radiation Absorption and Reprocessing in γ-Ray Binaries

Valentí Bosch-Ramon

Dublin Institute for Advanced Studies

Workshop on Variable Galactic Gamma-Ray Sources
Max-Planck-Haus, Heidelberg

1/12/2010

Outline

Outline

Gamma-ray binary systems: subclasses

- High-mass microquasars: massive star plus compact object that accretes forming jets.
- Pulsar high-mass binary: massive star plus pulsar with colliding winds.
- Massive star binary: two massive stars with colliding winds.

  (e.g. Aharonian et al. 2005a; Albert et al. 2006; Acciari et al. 2008; Tavani et al. 2009a, 2009b; Abdo et al. 2009, 2010a)
- Low-mass WD binary (V407 Cygni)
- Low-mass (ms) pulsar binaries (J102347.6+003841)

  (Abdo et al. 2010b; Tam et al. 2010)

Detected gamma-ray binaries with massive companions

- Three gamma-ray binaries have been detected in both the GeV and the TeV range: LS 5039, LS I +61 303 and PSR B1259$-$63.

  (Aharonian et al. 2005a, Albert et al. 2006, Acciari et al. 2008)

- Cygnus X-1 could be a TeV emitter as well...

  (Albert et al. 2007)

- Other candidates: HESS J0632+057, HD 215227 / AGL J2241$+$4454.

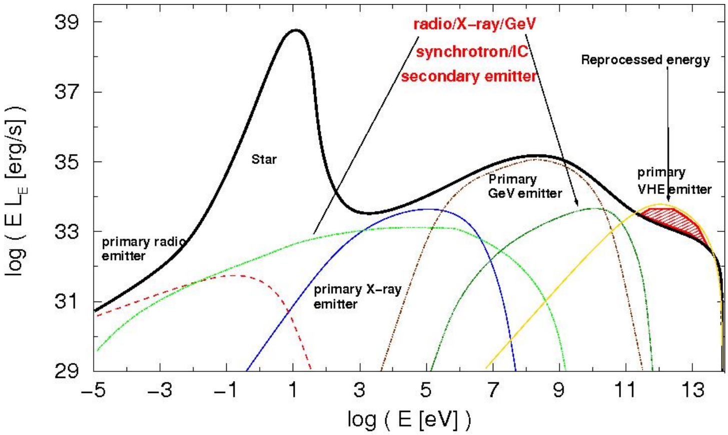
  (Hinton et al. 2009, Skilton et al. 2009, Falcone et al. 2010; Williams et al. 2010)

- Cygnus X-3, ηCar and possibly Cygnus X-1 have been detected in GeV.

  (Tavani et al. 2009a,b; Abdo et al. 2009, 2010a; Sabatini et al. 2010)

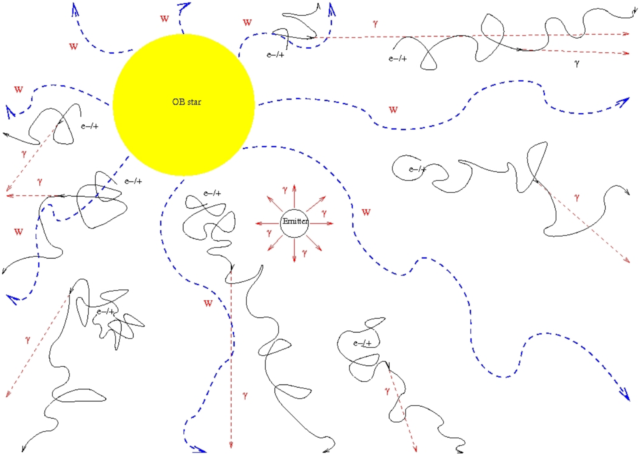
Outline

The non-thermal emission



Different components contribute to the non-thermal spectrum in gamma-ray binaries, of primary (accelerated particles) and secondary nature (gamma-ray absorption, hadronic process...).

Sketching the physical system

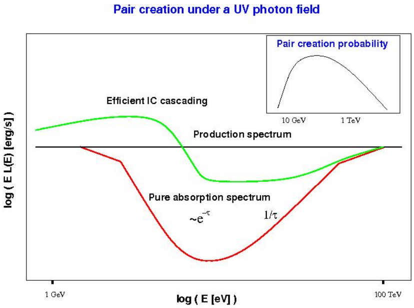


Gamma-rays produce pairs in the system that get deflected and confined in the stellar wind, moving with it, radiating and cooling down.

Outline

Pair creation

- Pair luminosity:
  $\propto (1 - \exp^{-\tau}) \sim$
  $(1 - \exp^{-0.5\, L_{*38}\, d_{*12.5}^{-1}}) \sim 1$
- Energy threshold:
  $E_{\rm th} \sim 2/E_{*}(1 - \cos\theta) \sim 1/E_{*}$
  (pair distribution maximum)
- Interaction probability:
  $\propto (1 - \cos\theta)$ (most of pairs toward the target source)



Relevant timescales

- **Stellar IC scattering (Th.):** $t_{\rm cool} \geq 55\, L_{*38}^{-1}\, E_{10\ {\rm GeV}}^{-1}$ s
- **Synchrotron emission:** $t_{\rm sync} \sim 400\, B_{10}^{-2}\, E_{10\ {\rm GeV}}^{-1}$ s
- **Adiabatic cooling:** $t_{\rm ad} \sim 2 \times 10^4 d_{12.5*}$ s
- Relativistic Bremsstrahlung: $t_{\rm br} \sim 10^6\, n_{\rm w9}^{-1}$ s
- Ionization cooling: $t_{\rm ion} \sim 3 \times 10^7\, E_{10\ {\rm GeV}}\, n_{\rm w9}^{-1}$ s
- **System light crossing time:** $t_{\rm l} = 100\, d_{12.5}$ s
- **Diffusion time:** $t_{\rm diff||} \approx 10^{-3}\, E_{10\ {\rm GeV}}\, \delta B_{\rm G}^{-1}$ s

Confinement/radiation regime

- $d_*/c < t_{\rm diff||} < t_{\rm rad}$: no isotropization, unefficient radiation
- $d_*/c < t_{\rm rad} < t_{\rm diff||}$: no isotropization, unefficient radiation

- $t_{\rm diff||} < d_*/c < t_{\rm rad}$: isotropization, adiabatic/radiation cooling
- $t_{\rm diff||} < t_{\rm rad} < d_*/c$: isotropization, efficient radiation

- $t_{\rm rad} < d_*/c < t_{\rm diff||}$: no isotropization, efficient radiation
- $t_{\rm rad} < t_{\rm diff||} < d_*/c$: no isotropization, efficient radiation

Stellar wind magnetic field and particle confinement

- Beyond the Alfven surface, $\sim 1-2\,R_*$, the magnetic field becomes dynamically dominated by the wind material.
- At few R_*, $B_\phi \propto d_*^{-1}$ becomes dominant over $B_{\rm r} \propto d_*^{-2}$.

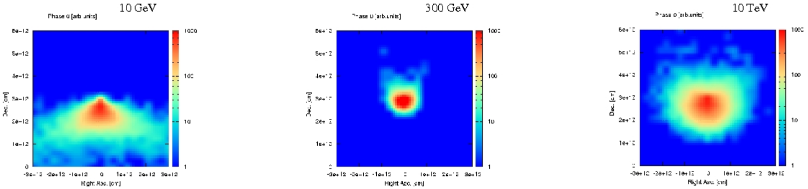
  (e.g. Usov & Melrose 1992)
- The condition of confinement, $t_{\rm diff||} < d_*/c$ requires $\delta B > 10^{-5}\,E_{10\ \rm G}\,d_{*12.5}$ G.
- Effective suppresion of cascades requires $B > 2\,L_{*39}^{1/2}\,d_{*12.5}^{-1}\,E_{\rm TeV}^{-0.85}$ G.

General properties

- Luminosities:
  - $L_{\mathrm{e}^\pm,\mathrm{IC}} \sim 5\times10^{-11}\,L_{\gamma35}\,L_{*38}\,d_{*12.5}^{-1}$ erg cm^{-2} s^{-1}
  - $L_{\mathrm{syncX}} \sim 10^{-11}\,L_{\mathrm{e}^\pm35}\,B_{10\,\mathrm{G}}^2\,L_{*38}^{-1}$ erg cm^{-2} s^{-1}
  - $L_{5\ \mathrm{GHz}} \sim 4\,L_{\mathrm{e}^\pm35}\,B_{\mathrm{G}}$ mJy (2 kpc)
- Spectrum (naively...):
  - above E_{th}, flat (synch.) and steep (IC)
  - below E_{th}, $\propto \nu^{-1.5}$ (synch./IC)
- Variability: geometry, $L_\gamma(E_\gamma)(\phi,t)$, B, wind inhomogeneities/anisotropies
- Morphology: spiral like/elongated at low energies, dependent on the eccentricity and the wind anisotropies/inhomogeneities, other outflows...

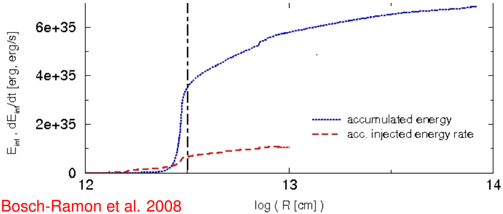
Outline

Spatial distribution of pairs



Bosch-Ramon & Khangulyan 2010, sub.

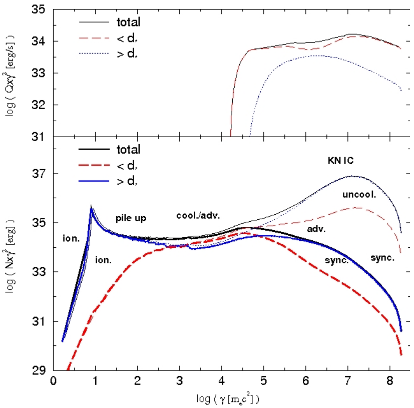
- Pairs distribute in the system depending on their energies.
- Significant amount of energy accumulate in the wind at scales of the binary system.



Bosch-Ramon et al. 2008

Energy distribution of pairs

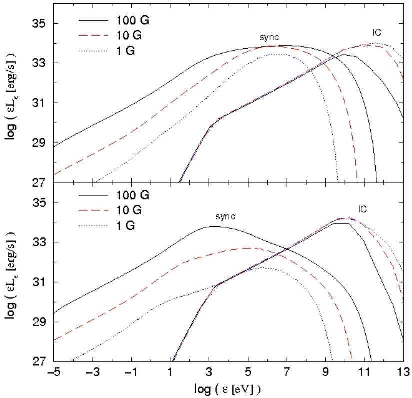
- $Q(E_{\rm th} \propto \sigma(E_\gamma)_{\rm UV}$ ->
  - $N(E < E_{\rm th}) \propto E^{-2,-1}$ (Th. IC/synch. vs adiabatic)
  - $N(E > E_{\rm th}) \propto Q(E)\, E^{+1,-1}$ (KN IC vs synch.)
- Pairs from different regions have different spectra.



Bosch-Ramon et al. 2008

The radiation spectral energy distribution

- For high B the synchrotron SED peaks at X-rays.
- The IC component peaks around 10 GeV, strongly softening at higher energies.
- For low B, KN IC cooling hardens all the spectra strongly $\rightarrow$ IC cascade

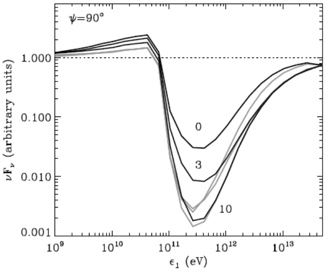


Secondaries can *violate* the synch. $\nu_{\max}$-limit at $\sim$ 100 MeV.

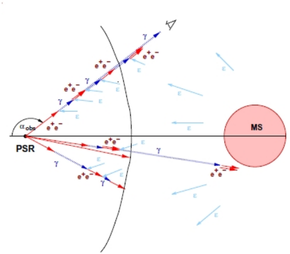
Bosch-Ramon et al. 2008

Efficient cascading

- Very low B ($B \ll 10^{-3}\,(E_{\rm TeV}/d_{*12.5})$ G): 1 D
- Fairly low B ($B \ll 1\,(L_{*39}/d_{*12.5})$ G): pure 3 D
- Intermediate cases: $L_{\rm TeV} \propto B^{-2}$



(Cerutti et al. 2010)

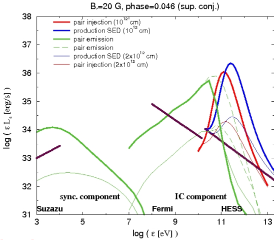


(Sierpowska-Bartosik & Torres 2008)

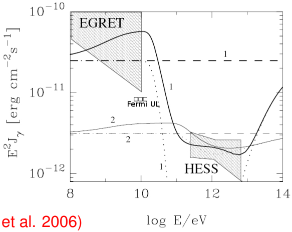
(see also Aharonian et al. 2006; Orellana et al. 2007; Khangulyan et al. 2008; Bosch-Ramon et al. 2008; Bednarek 2010)

The case of LS 5039 (I)

- Efficient gamma-ray production inside the binary system can easily violate the X-ray and GeV fluxes.
- A pure 3D IC cascade model cannot explain the data above GeV in LS 5039.
- Photon-photon absorption cannot play a dominant role → system periphery emitter



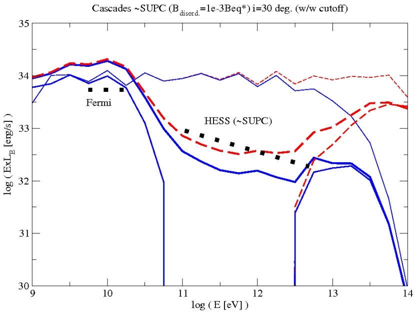
preliminary

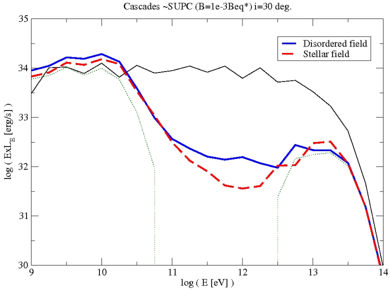


(Aharonian et al. 2006)

The case of LS 5039 (II)

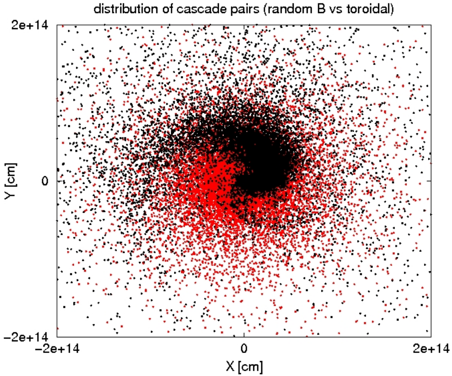
Another exemple of a 3D cascade (low *B*) at SUPC in LS 5039

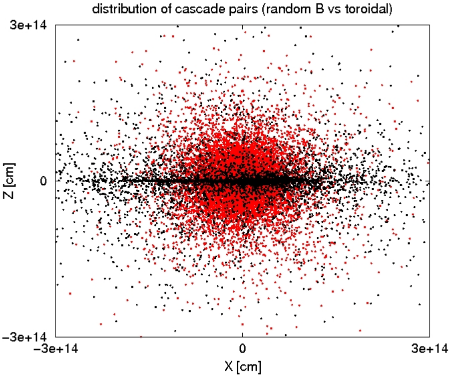




preliminary

Pair distribution: stellar vs disordered *B*

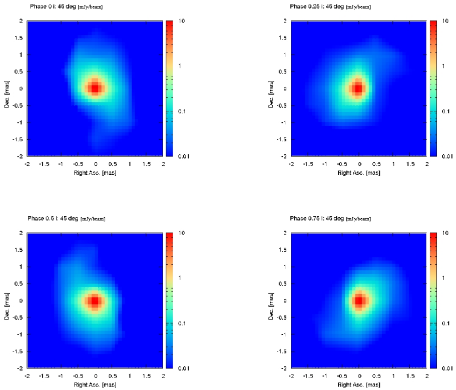




Diffusion spreads up/downwards, but confines sidewards.

Radio emission from secondary pairs in gamma-ray binaries

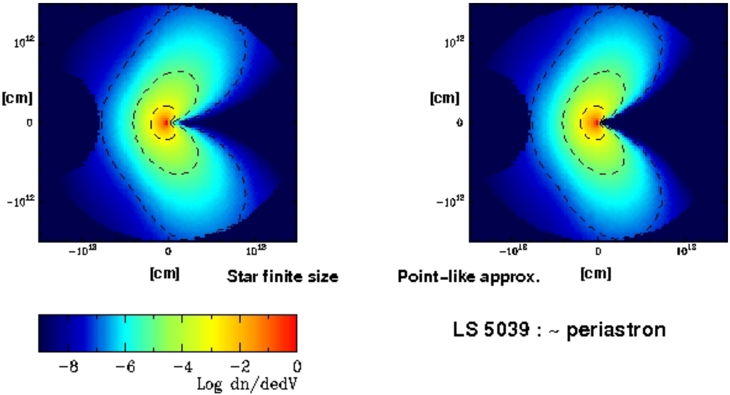
5 GHz emission in the observer plane produced by secondary pairs created in a gamma-ray binary.



Bosch-Ramon & Khangulyan 2010, sub.

Pair injection: point-like versus finite size

For secondary radio emission the star point-like approximation is fairly good.



Bosch-Ramon & Khangulyan 2010, sub.

Outline

Summary

- Gamma-rays with $E_\gamma > 10$ GeV fill the binary system.
- Pairs are created under the presence of a dense (stellar) photon field.
- Confinement of particles is likely efficient (isotropic pair distribution, 3D cascades).
- For moderate magnetic fields:
  - Cascades get suppressed
  - X-ray emission can overcome the observed fluxes $\rightarrow B_{\rm X} \lessapprox 10$ G.
- In LS 5039, absorption nor cascades should be dominant.

Open questions: localization/extension of the emitter, *B* geometry, *B* in radio regions, impact on the wind...