The spectral energy distribution of γ-ray binaries

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Outline

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1. Introduction
2. The spectral energy distribution of gamma-ray binaries
3. Basic analysis of the gamma-ray emission
4. Relevance of pair creation
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Detected gamma-ray binaries

- Three gamma-ray binaries have been detected in both the GeV and the TeV range: LS 5039, LS I +61 303 and Cygnus X-1 (?).

  (Abdo et al. 2009a, 2009b, Sabatini et al. 2010; Aharonian et al. 2005a, Albert et al. 2006, 2007)

- PSR B1259$-$63 and HESS J0632+057 (?) have been detected above 100 GeV, but not below.

  (Aharonian et al. 2005b; Albert et al. 2007; Aharonian et al. 2007)

- Cygnus X-3 has been detected in the GeV band, but not at TeV energies.

  (Tavani et al. 2009, Abdo et al. 2009c, Saito et al. 2009)

- η-Carina could have been detected only in the GeV range.

  (Tavani et al. 2009)

Gamma-ray binary systems: subclasses

- High-mass microquasars: massive star plus compact object that accretes forming jets.

  (e.g. Bosch-Ramon et al. 2006, Orellana et al. 2007, Araudo et al. 2009)

- Pulsar high-mass binary: massive star plus pulsar with colliding winds.

  (e.g. Dubus 2006, Chernyakova et al. 2006, Sierpouska-Bartosik & Torres 2008)

- Massive star binary: two massive stars with colliding winds.

  (e.g. Benaglia & Romero 2003)

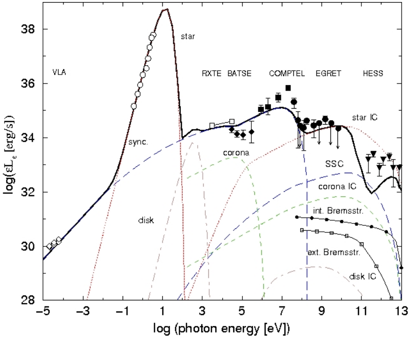
- Other possible sources: low-mass microquasar, accreting pulsar high-mass X-ray binary, WD binaries (?)...

  (e.g. Romero & Vila 2008, Sguera et al. 2009)

Outline

The spectral energy distribution

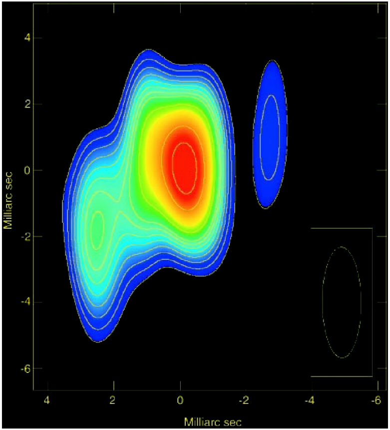
- Radio emission: synchrotron
- IR-Optical-UV: primary star
- X-rays: synchrotron/IC scattering
- gamma-rays: IC/hadronic processes



LS 5039: Paredes et al. 2006

Radio emission

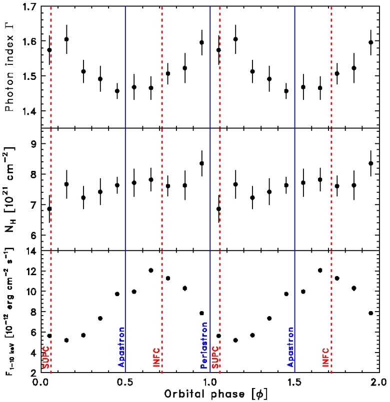
- Flat-steep spectrum.
- Variable and periodic.
- Scales:
  core (< 10 AU)
  mas ($\sim 1 - 10$ AU)
  100 mas ($\sim 10^2 - 10^3$ AU)
  $> 1''$ ($> 10^3$ AU)



LS 5039: Paredes et al. 2000

X-rays

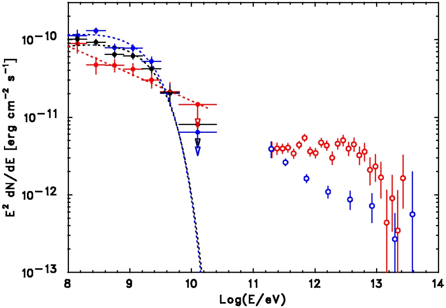
- Hard spectrum/accretion disk-like.
- Variable and periodic
- Scales:
  core (binary system)
  $\sim 10''$? ($\sim 10^4 - 10^5$ AU)



LS 5039: Takahashi et al. 2009

Gamma-rays

- Photon index $\Gamma \sim 2-3$
- Variable and periodic
- Scales:
  binary system ($<$ AU)
  flow termination?
  ($\sim 1-10$ pc)

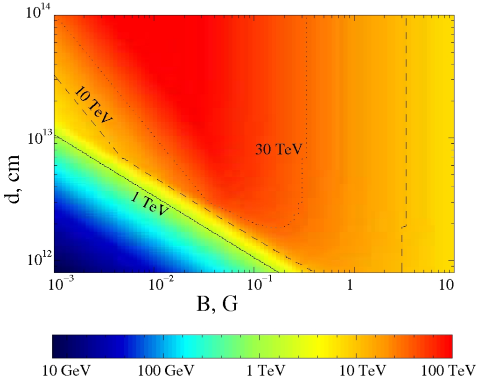


LS 5039: Abdo et al. 2009

Outline

Acceleration efficiency

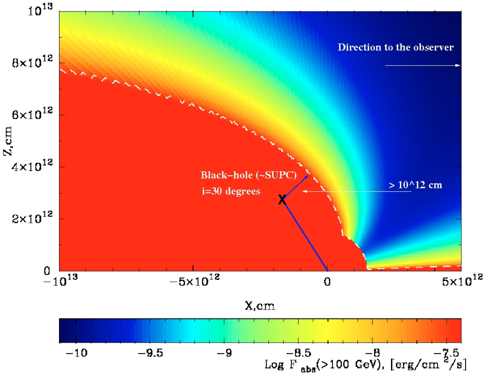
- The location, the efficiency, and the magnetic field of the accelerator can be studied using data constraints.



LS 5039: Khangulyan et al. 2008

Absorption maps

- The location of the VHE emitter can be constraint studying the gamma-ray opacity.



Cygnus X-1: Bosch-Ramon et al. 2008

The gamma-ray radiation mechanism

- IC scattering (KN):

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

- *pp* collisions:

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

- $p\gamma$ interactions (threshold!):

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

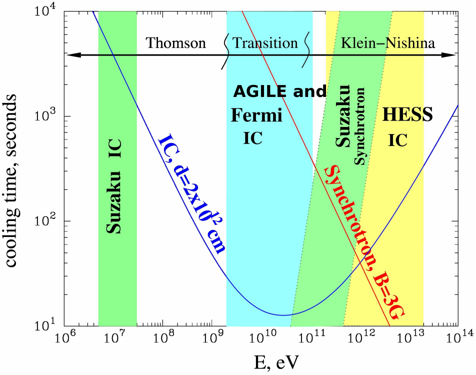
- Photo-disintegration (threshold!):

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

(Bosch-Ramon & Khangulyan 2009)

The synchrotron and IC scenario

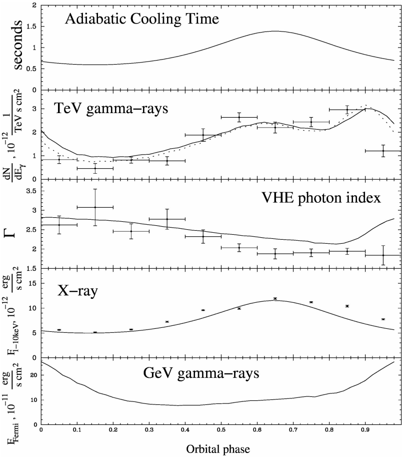
- The more efficient mechanism is IC: smaller energetics and acceleration constraints.
- Could one-zone models explain the X-ray and TeV fluxes with the same population?



LS 5039: Takahashi et al. 2009

One-zone models

- LS 5039 is the best studied gamma-ray binary.
- It is a very complex source: periodic emission, very efficient particle acceleration, gamma-ray absorption, huge energetics.
- Modeling hints the physical conditions, but, energy budget, environment, transport...?

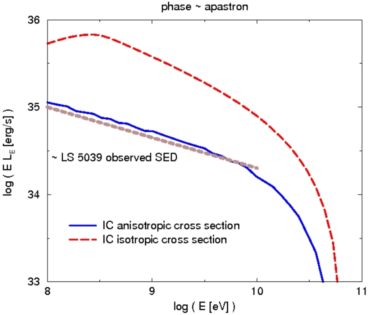


LS 5039: Takahashi et al. 2009

(for LS I +61 303: Zabalza et al., in prep.)

IC energy budget

- From $L_{\rm nt} = 3 \times 10^{36}$ erg s^{-1} and $\epsilon_{\rm nt} \sim 0.1 \rightarrow L_{\rm T} \sim 3 \times 10^{37}$ erg s^{-1}.
  - Pulsar scenario: $L_{\rm T} \sim 0.1\, L_{\rm crab}$, with $t_{\rm src} \sim 10^3 - 10^4$ yr; pulsations, SNR?
  - Black hole scenario: $L_{\rm T} \geq 0.1\, L_{\rm Edd\odot}\, (M/3\, M_{\odot})^{-1}$; accretion radiative efficiency?
  - Environmental impact: stellar wind or ISM/outflow interactions?



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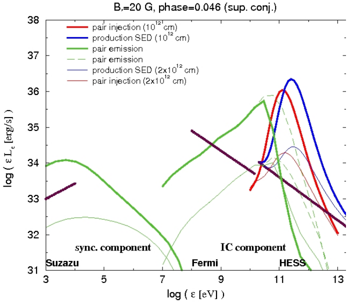
Pair creation: secondary emission

- In the UV stellar photon field VHE photons are absorbed ($\tau \gg 1$).
  (Ford 1984; Dubus 2006; Khangulyan et al. 2008; Reynoso et al. 2008)
- Created pairs can be quickly deflected: $t_{\rm iso} \sim t_{\rm IC\ cool}/10$ at 100 GeV and $B = 1$ G.
- Created pairs radiate via synchrotron and IC emission.
- Secondary emission and X-ray and GeV data combined can give strong constraints on the emitter location.

Pair creation: Periastron/Superior conjunction

- Around periastron/SUPC and $B_* = 20$ G ($B \sim$ few G), an emitter location $Z < R_{\rm orb}$ violates the X-ray/GeV constraints.
- Unless $B_* \ll 20$ G, EM cascades are already supressed.



Bosch-Ramon et al., in prep.

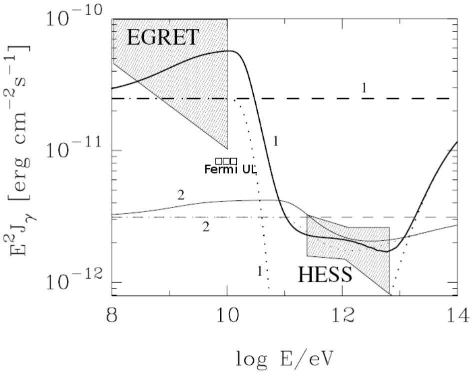
Pair creation: EM cascading

- If $u_{\rm B} \ll u_*$, created pairs with $E \gg E_{\rm th}$ produce gamma-rays...
- ...subject to photon-photon absorption/pair creation.
- For high τ values, an EM cascade develops.

  (Akharonian & Vardanian 1985; Bednarek 1997; Khangulyan et al. 2008; Sierpouska-Bartosik & Torres 2008)

Electromagnetic cascading in LS 5039

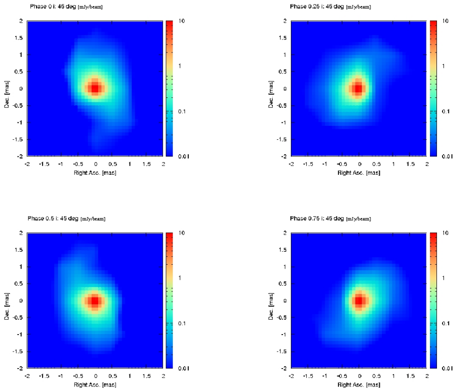
Pure cascading around SUPC violates Fermi data.



Aharonian et al. 2006

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.

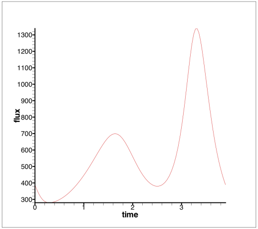


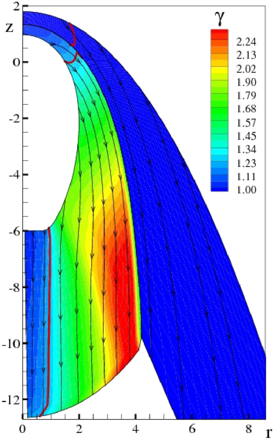
Bosch-Ramon & Khangulyan 2010, sub.

Outline

Star/pulsar colliding winds

- The collision of the pulsar wind with the stellar wind leads to the formation of a powerful supersonic relativistic backflow.



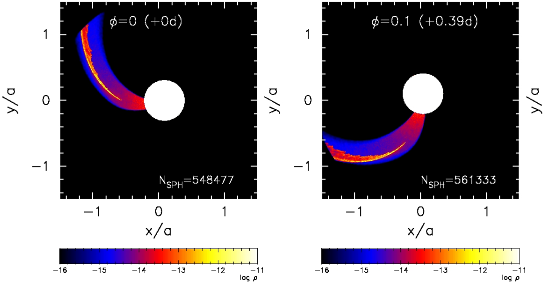


Bogovalov et al. 2008

Bogovalov et al., in prep.

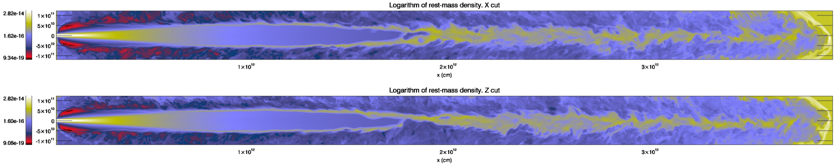
Accretion

- The accretion rate in LS 5039 is similar to the Bondi-Hoyle rate.



Okazaki et al. 2008

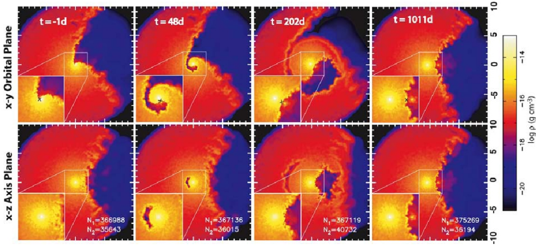
A jet crossing the dense stellar wind in a HMMQ can be disrupted before reaching radio detectable distances. Particles can be accelerated in the interaction shocks.



Perucho et al. 2010; see also Bordas et al. 2009

Massive star colliding winds

- Colliding powerful and fast winds in close massive star binaries can lead to particle acceleration and gamma-ray IC emission.



Okazaki et al. 2009

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Final remarks

- Presently, gamma-ray binaries comprehend microquasars, pulsar massive binaries and massive star binaries.
- The spectral energy distribution of gamma-ray binaries arises from synchrotron and IC emission under the impact of adiabatic cooling and effective transport.
- Photon-photon absorption can have a strong impact at: gamma-rays (attenuation + reprocessing) and lower energies (reprocessing).
- To understand the dynamics of the emitter and the role of the environment requires MHD calculations (energy budget?).
- Characterizing the emitter, and in some cases, solving the nature of the compact object, are primary goals in the gamma-ray binary study.