 Gamma-ray emission from X-ray binaries: two classes

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Alternative models for very energetic γ-ray binaries. (Left) Microquasars are powered by compact objects (neutron stars or stellar-mass black holes) via mass accretion from a companion star. This produces collimated jets that, if aligned with our line of sight, appear as microblazars. The jets boost the energy of stellar photons to the range of very energetic γ-rays. (Right) Pulsar winds are powered by the rotation of neutron stars; the wind flows away to large distances in a comet-shaped tail. Interaction of this wind with the companion-star outflow may produce very energetic γ-rays.

Mirabel 2006
X-ray binaries emitting high-energy $\gamma$-rays

- **PSR B1259–63**, a young radio pulsar + Be star;
- A number of similar persistent sources, e.g., **LS I +61 303**, **LS 5039** (well studied), and **HESS J0632+057**, **HESS J1018-589/1FGLJ1018-58567**, all with the broad-band spectra similar to that of PSR B1259–63;
- The accreting X-ray binary **Cyg X-3**. GeV emission modulated at the orbital period seen by **Fermi** during radio outbursts.
- The accreting black-hole binary **Cyg X-1**. Possible transient GeV and TeV emission observed by **AGILE** and **MAGIC**, respectively. New results from **Fermi**.
Part I

Colliding wind binaries (a neutron star + a high mass star)
The three well-studied persistent TeV-emitting binaries:

- They are high-mass, eccentric, Be/O binaries.
- One of them, PSR B1259–63, is a radio pulsar which wind interacts with the Be wind, which gives rise to the $\gamma$-ray emission.
- The other two systems, LS I +61 303 and LS 5039, have properties similar to PSR B1259–63, and likely also contain young pulsars (e.g., Dubus 2006; Z., Neronov, Chernyakova 2010).
- The colliding pulsar/stellar wind model was proposed by Maraschi & Treves (1981) for LS I +61 303. Accretion is then inhibited by the pressure of the pulsar wind.
They look very similar to each other. PSR B1259–63 is a 48-ms radio pulsar with a Be companion, in which the wind of the pulsar interacts with the wind of the Be star around periastron.
The radio-pulsar model

- A young neutron star loses its rotational energy energy at \( \sim 10^{36} \text{ erg s}^{-1} \) and generates pair plasma at \( \gamma \sim 10^{(5-6)} \) moving away from the pulsar and colliding with the wind from the Be/O star. This results in a shock, which randomizes and accelerates the pairs.

- The relativistic pairs lose energy and emit radio synchrotron radiation and inverse Compton emission off the stellar optical photons.
Emission from collision of winds and the wind nebula

Bednarek & Sitarek 2013
Spectral models of LS I +61 303

Two inhomogeneous wind models with electron acceleration. In one, radio is synchrotron, keV–GeV are Compton, and the variable TeV spectrum is not modelled. In the other, keV–GeV are synchrotron, and TeVs are Compton. The actual model may be a superposition of the two. See also Bednarek 2011, Bednarek & Sitarek 2013.
Part II

Accreting black-hole binaries
Accreting black-hole binaries (microquasars)

- The X-ray spectra of all known black-hole binaries fall into well-defined states (hard/soft), depending primarily on $L/L_E$.
- This appears to be a consequence of astrophysical black holes being characterized only by mass and spin.
- All accreting X-ray binaries are $\gamma$-ray quiet, i.e., either they are not detected in $\gamma$-rays or $L_\gamma < L_X$. 
A likely geometry of the soft state:

inherently nonthermal

cold accretion disk

active region

reflected photons

gravity

soft seed photons

hard photons

intermittent jet

scattered hard photons

The inner disc radius probably at the innermost stable orbit, $6GM/c^2$ or less for a rotating black hole
A likely geometry of the hard state:

- jet emitting radio/IR/O...
- scattered hard photons
- scattered reflected photons
- direct soft photons
- cold outer disk
- hot inner disk
- thermal plasma with $kT_e \sim 50$–150 keV
- gravity + Coulomb
- black hole

The inner disc radius poorly determined, $\sim 10$–200$GM/c^2$, $L/L_E$ dependent
II.1. Discovery of GeV γ-rays from Cyg X-3

- It is very luminous radio and X-ray source, WR donor + a black hole or (less likely) a neutron star, the unusually short (for HMXBs) period of 4.8 h.
- The X-ray spectra similar to those of spectral states of black-hole binaries.
- This is only certainly accreting X-ray binary with certain emission at >0.1 GeV, detected by *Fermi* and *AGILE*. 
Observations by *Fermi*, 0.1–10 GeV

The emission from the pulsar PSR J2032+4127 has only narrow pulses, which intervals are removed from the data for Cyg X-3, which results in a loss of only 20% of the Large Area Telescope exposure.

PSR J2032+4127 30' away from Cyg X-3
Observations by *Fermi*, 0.1–10 GeV

Abdo+ 2009

Strong correlation with the radio emission, suggesting the gamma-ray emission is from a jet.
Observations by *Fermi*, 0.1–100 GeV

Orbital modulation of γ-rays during the active periods. The γ-rays have the *maximum* close to the superior conjunction.

But the X-rays undergo wind absorption, thus the minimum $F$ is at the superior conjunction (black hole behind the donor).

*Abdo et al.* 2009
A model for the modulated GeV emission

**Compton anisotropy**

- The relativistic electrons in the jet Compton upscatter stellar photons to GeV energies.
- Highest scattering probability for electrons moving towards the star.
- Relativistic electrons emit along their direction of motion.
- Thus, most of the all emission is toward the star. The maximum of the observed emission is when the jet is behind the star.

Dubus, Cerutti & Henri 2010
Constraints from the data: $N(\gamma) \propto \gamma^{-(3.5-4)}$, $\gamma_{\text{min}}>1000$ in the emitting part of the jet. The acceleration index $\Gamma \geq 2.5$. The jet magnetic field $\ll$ equipartition, $B<10^2 \text{G}$.

See also Sitarek & Bednarek 2012
The down-stream electron spectrum: a sharp break above $\gamma > 300$, i.e., a fraction of the proton/electron mass ratio; steep slopes of accelerated electrons.
II.2. Cyg X-1. Some new results

- An accreting black-hole binary. Donor: OB supergiant. $P = 5.6$ d, $d \approx 1.9$ kpc, $M_{\text{BH}} \approx 15 \, M_\odot$.
- Wind accretion, the donor nearly fills its Roche lobe.
- Emission from radio (resolved by VLBA) to MeV.
Accretion models of X-rays/γ-rays of Cyg X-1

A hot Compton-scattering plasma with thermal electrons and a nonthermal tail

The current Fermi upper limits do not impose constraints on the hard state models. In the soft state, pair absorption in γγ collisions constrains the source size.

Z., Chernyakova & Malishev 2013
The MeV tail in the hard state be from optically-thin jet emission. Relativistic electrons in the jet Compton scatter both the synchrotron and stellar emission → high-energy \( \gamma \)-rays. The upper limits → \( B > 10^5 \) G at the jet base of \( z > 2 \times 10^3 R_g \).
Summary

- Gamma-ray loud binaries, emitting in TeV: colliding pulsar wind + stellar wind from an Be/O star. Extended and complex gamma-ray emission region. Multiple radiative processes.
- Soft state of Cyg X-3: The jet is launched close to black hole, but it propagates without radiating up to $R \sim 10^6 \ R_g$, where electrons are accelerated with a steep power-law above $\gamma_{\min} \sim 10^3$. The GeV emission is from upscattering of blackbody photons. Intersection of the accretion and jet components in the MeV region.
The high-energy $\gamma$-ray emission takes place only during soft X-ray states.

Spectral states (similar to those of bh binaries)

The flares detected by AGILE

Szostek+ 2007
The radio-pulsar model

Cerutti, Dubus & Henri 2009