High energy processes in binary systems

Andrzej A. Zdziarski
Centrum Astronomiczne im. M. Kopernika
Warszawa, Poland
Binaries with high-energy EM emission

- Binaries powered by accretion onto a black hole or neutron star; emission of both the accretion flow and jet (covered in this talk).
- So-called gamma-ray binaries, defined by the peak of their \( \nu F_{\nu} \) spectrum at GeVs: pulsar wind colliding with stellar wind from a high-mass star (powered by pulsar rotation).
- \( \gamma \)-ray emitting pulsars in binaries: recycled ms pulsars spun up by accretion, but no longer accreting (powered by pulsar rotation); in some cases pulsar wind ablating the low-mass companion \( \rightarrow \) the wind interacting with the companion.
- Colliding-wind binaries: collision of stellar winds from two massive stars;
- Novae: thermonuclear runaway on a white dwarf, high-energy emission due to particle acceleration in the ejecta.
- Coalescence of NS-NS and NS-BH binaries: jets and ejecta.
Accreting stellar binary systems with a compact object (black hole or neutron star)

An accreting binary. The donor: either a high or a low-mass star.

Binaries containing a BH and a massive donor are persistent, and those with a low-mass donor are mostly transient (outbursts separated by years of quiescence).

Mirabel 2012
Cyg X-1, a black hole+OB supergiant binary

- MeV high-energy tails (probably from accretion) in both the hard and soft states.
- High-energy $\gamma$-rays in the hard state only emitted by the jet seen in the radio to mm.
- The presence of a jet only in the hard state only is characteristic to most of known accreting BH binaries.
Disc/corona geometry of the soft state:

no jet  
(except for Cyg X-3)

gravity

cold accretion disk

active region

reflected photons

soft seed photons

scattered hard photons

black hole

The inner disc radius at the innermost stable orbit
The truncated disc model for the hard state:

- **Cold outer disk**
- **Hot inner disk**
- **Thermal plasma with** $kT_e \sim 50–150$ keV
- **Gravity + Coulomb**
- **Reflected photons**
- **Direct soft photons**
- **Scattered hard photons**
- **Jet emitting radio/IR/O...**

The inner disc radius $\sim 10–200 \ GM/c^2, L/L_E$ dependent.
The jet contribution to the hard-state spectrum of Cyg X-1

A jet model with electron acceleration, cooling, electron transport, all radiative processes. Compton scattering of stellar blackbody and SSC dominate the $\gamma$-ray emission.

Electron acceleration from $z_{\text{acc}} \approx 100 \, R_g$, at which distance $B \approx 8 \times 10^4 \, \text{G}$. 

(AAZ+ 2014a,b, 2017; Malyshev+ 2013)
Cyg X-3: a compact object and a WR donor

High-energy emission detected in the soft state only. Electron acceleration above $\gamma_{\text{min}} \sim 10^3$ with an index $\Gamma \approx 2.5$, Compton scattering of the donor blackbody photons. The GeV emission strongly modulated on the orbital period.

X-ray spectra in different states

$\gamma_{\text{min}} = 1300$, $\Gamma_{\text{inj}} \approx 2.5$

AAZ+ 2012, 2018
A model for the modulation of jet $\gamma$-ray emission

**Compton anisotropy**

- The relativistic electrons in the jet Compton upscatter stellar photons to GeV energies.
- Highest scattering probability for electrons moving towards the stellar photons.
- 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+10, AAZ+18
Fits of this model to the folded $\gamma$-ray light curve

The distance along the jet from the compact object to the $\gamma$-ray emission region $\approx 3 \times$ the stellar separation, $\sim 10^{12} \text{ cm} \sim 10^6 R_g$. The jet is inclined w/r the binary axis, $\theta \sim 30^\circ$, and its velocity is $\geq 0.3c$. 

AAZ+18
Correlations and time lags

• 15 GHz radio: no lag w/r to soft X-rays in the hard spectral state, but a 45–50 d lag in the soft state.
• Corresponding anticorrelations with hard X-rays.
• The origin of the lags: probably the time needed for magnetic field accumulation in the disc.
A model for the ~40–50-d lag of radio w/r to X-rays

- Advection of magnetic field from the companion in a disc:

\[ \tau_{\text{adv}} = \tau_{\text{dif}} \text{ yields} \]

\[ \tau_{\text{accum}} \sim \frac{R_d}{|v_r(R_d)|} = 5.7 \times 10^{-11} \alpha^{-1} \left( \frac{H}{R_d} \right)^{-1} P_m \kappa_0 m r_d^{3/2} \text{ day} \]

Cao & AAZ 2019
High-energy processes in jets of accreting binaries

- Jet launching and bulk acceleration close to the BH without dissipation.
- Acceleration of electrons to relativistic energies at large distances, up to millions of gravitational radii.
- Synchrotron and Compton emission; $\gamma$-rays from Compton scattering of blackbody photons and synchrotron self-Compton.
- Hadronic processes, e.g., pion production, do not contribute to the observed spectra, as shown, e.g., by the strong orbital modulation of the GeV emission in Cyg X-3 (also in Cyg X-1; modelled by Compton scattering of the donor blackbody).
- $\gamma$-rays observed so far up to some tens of GeV (except for one transient TeV emission event at a low significance). But TeV emission should be detected by CTA.
The nature of viscosity

- Matter accretes through the disc due to the magnetorotational instability (MRI; Balbus & Hawley 1991), which transfers the angular momentum outward. Initially, only some small residual magnetic field is required.
- It works for both hot and cold discs.
- The magnitude of the MRI viscosity depends on the presence of large-scale vertical magnetic field. It its absence, the viscosity parameter is \( \alpha \approx 0.01 \), but with a net field it can increase to \( \alpha \approx 1 \) (Bai & Stone 2013).
- But MRI by itself cannot form net vertical magnetic fields.
Two jet launching mechanisms

- Extraction of the spin energy of a rotating black hole (Blandford & Znajek 1977; Tchekhovskoy+2011; McKinney+2012, ...). \( P_{\text{jet}} \sim (a/M)^2 B_\perp r_g^2 c \).
- Collimation and acceleration by disc poloidal magnetic field (Blandford & Payne 1982). A lower jet power.
- Both mechanisms require the presence of a net vertical field.
What is the origin of the large-scale field?

• In AGNs, large scale field can be advected from coherent patches of the interstellar medium (e.g., Cao & Lai 2019).

• However, field advection in accreting binaries faces two major problems:
  – jets are present in the hard state but absent in the soft state, while an extended outer cold disc is present in both states. Advection through that disc should be the same in both states.
  – magnetic fields of donors vary strongly while the jet radio emission in various systems is tightly connected to the accretion rate.

• Can a net field be generated locally?
Two proposals to generate net vertical field locally in the hot accretion flow.

- (1) Begelman & Armitage 2014:
  - MRI generates closed field loops, also at the boundary of the hot (thick) and cold (thin) parts of the disc. The part of the loop in the cold disc diffuses away while the part in the hot disc is advected inward, which breaks the loop and creates a patch carrying vertical field with a random sign.
  - Accumulation of those patches in a random-walk like process leads to a build-up of some net flux with a given sign during a given occurrence of the hard state.

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Generation of net vertical field locally in the hot accretion flow

- (2) Parfrey, Giannios & Beloborodov (2015):
- A somewhat similar process, but the closed magnetic loops open up at the boundary of the accretion flow and the BH horizon due to their different rotation velocity.
- This creates fluctuating vertical fields above and below the BH, which also reconnect, leading to cycles of the energy flux through the BH surface:

- However, the process is efficient only for retrograde accretion, unlikely for accreting binaries.
Summary

- Accreting BH binaries feature a disc and a jet, of which the jet is the main source of high-energy emission.
- The high-energy jet emission is dominated by Compton upscattering by relativistic electrons accelerated to high energies of some soft photons, either stellar blackbody (in the case of high-mass donors) or synchrotron or both.
- In most of the BH binaries, the jet is present only in the hard spectral state, in which also a hot plasma emitting hard X-rays is present.
- The jet can be formed by net vertical magnetic field connected to either a rotating BH or an inner part of the accretion disc.
- The origin of the net vertical field is unclear; its presence is simply assumed in most of papers.
- Advection from the donor unlikely; some proposals to generate it locally, to be verified.