On the physics of the most luminous gamma-ray emitting binaries

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High Energy Phenomena in Relativistic Outflows VIII

Institut d’Astrophysique de Paris, Observatoire de Paris
October 23, 2023
Outline

1. Introduction
2. Binary scales
3. Beyond binary scales
4. Discussion
Talk focus

- Focus on high-mass $\gamma$-ray binaries (HMGB) with NS/BH + relativistic outflow (see right).
- We will not discuss phenomenology (orbit, SED, lightcurves, morphology...); examples:
- We will not discuss other related classes (rel. LMGB, massive star binaries, novae...).
- We will discuss physical processes underlying the non-thermal activity.
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  \begin{itemize}
    \item (Paredes et al. 2000; Casares et al. 2005a; Aharonian et al. 2006; Takahashi et al. 2009; Hadasch et al. 2012; Chang et al. 2016; Yoneda et al. 2021)
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Motivation

- Large NT power: at least $\sim 10^{37}$ erg s$^{-1}$ (or more) in most of the sources.
- Acceleration rates close to $\sim qBR$ for $e^{\pm}$, up to $\sim 100$ TeV, on binary scales (mostly).
- Interplay of orbit, $V_{ISM}$, outflow/medium interaction leads to rich physics.
- Binary and large scale non-thermal activity (synchr., IC, CR... even $\nu$?).

(Koljonen+23 ↑; Khangulyan+08 -LS 5039- ↓; Corbet+16 -LMC P3- →)

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Relevant physical factors

- Relativistic HMGB, accreting or not, are the most luminous $\gamma$-ray emitting binaries and share the most important elements:
  - Relativistic outflows (winds and jets).  
  - Dense radiation field.
  - Substantial and structured stellar wind.
  - Relativistic effects.
  - Shocks, instabilities and mixing.
  - Magnetic fields.
  - Orbital motion and eccentricity.

(BINARY SCALES)

(B-EYOND BINARY SCALES)

- Large scale interactions.

(B-R & Barkov 2016 -MQ-)

(Zabalza et al. 2013-PSR-)

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In a HMMQ:

- A jet can form, protected from the stellar wind by an accretion wind.
- Magnetization, content, and velocity are unclear, possibly structured.
- The jet can already suffer internal or recollimation shocks, and mass-load.

In a non-accreting pulsar:

- Pulsar wind likely magnetized, anisotropic, and ultrarelativistic.
- The pulsar wind is accelerated by $B$ dissipation; how fast is it?
- Highly relativistic unshocked flow in a dense photon field plus $e^\pm$-creation:
- IC and 1-shot converter mechanism?

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Radiation fields

- **Strong IC:** $u_* \sim 1 - 100 u_B(L_*,38/L_{0,36})$
- Radiation efficient even in binary periphery.
- On binary scales, $\tau_{\gamma\gamma uv} \sim 0.1 - 10$ but...
- ...there is no clear evidence of radiation reprocessing in radio, X-rays, gamma rays.
- Photo-hadronic processes if $\exists 0.1-10$ PeV $p$/nuclei on binary scales ($q_{BR} \lesssim$ PeV).

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Substantial and structured stellar wind

- Massive star wind determines dynamics:
  - \( \frac{L_0}{\dot{M} c} \approx 5 \times 10^7 \left( \frac{L_{0,36}}{\dot{M}_{-7}} \right) \text{ cm s}^{-1} \),
  - \( \sqrt{2L_0 / \dot{M}} \approx 5 \times 10^8 \sqrt{\frac{L_{0,36}}{\dot{M}_{-7}}} \text{ cm s}^{-1} \).

- The winds are complex:
  - There is a fast, clumpy polar wind.
  - Be star has dense slow disk but \( \rho \propto r^{-3} \).

- The wind can affect/mix with relativistic flow.
- Dense wind+mixing might lead to efficient \( pp \).
- Sill, \( \frac{L_0}{L_{sw}} \sim 10 \left( \frac{L_{0,36}}{\dot{M}_{-7}} v_{w,8}^2 \right) \), so outflow determines the dynamics at large scales.

\( (\text{Perucho & B-R 2012-cl. MQ-}) \)

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Distorted CD
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- Dense wind+mixing might lead to efficient pp. (Romero+03)

- Sill, \( \frac{L_o}{L_{sw}} \sim 10 \left( \frac{L_{o,36}}{\dot{M}_{-7}} v_{w,8.3}^2 \right) \), so outflow determines the dynamics at large scales. (Romero+03)

(Oakazaki et al. 2011-Be PSR-)

(Perucho & B-R 2012-cl. MQ-)

(Kefala & B-R 2023-cl. PSR-)

V. Bosch-Ramon (UB)  On the physics of gamma-ray binaries  October 23, 2023  10/19
Relativistic effects and energetics

- Reduction/enhancement of target fields:
  \[ \epsilon'_0 = \delta_\star \epsilon_0, \quad u' \propto \delta_\star^2 u, \quad \delta_\star = \Gamma (1 - \beta \mu), \quad B' \approx B/\Gamma. \]

- Reduction/enhancement of observed emission:
  \[ L_{\text{obs}} = \delta_{\text{obs}}^3 L'/\Gamma. \]

- Observed emission shaped by anisotropy of particles and targets in flow frame, and L.O.S.

- Except for blazar-like jets, orbital modulation yields a (large) minimum NT power.

- Relativistic effects are likely confined to the binary scales due to stellar wind influence.

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Shocks, instabilities and mixing

- Jet/wind shocked from star side.
- Shocked flow soon gets unstable.
- In pure HD, R.-M., R.-T., and K.-H. instabilities are important.
- Instabilities+mixing on all scales.
- What is the role of $B$?

(Lamberts et al. 2013-PSR→)

(Barkov & B-R 2022-MQ↓)

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Magnetic fields

- **In winds, as $\sigma \sim 1$, postshock physics is affected:**
  - The anisotropic $P_B$ modifies size and geometry.
  - Flow direction and velocity are strongly modified.
  - Reconnection can occur in shocked flow current sheets.
- **In winds and jets, $B$ can both enhance or suppress instability.**

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Outline

1. Introduction
2. Binary scales
3. Beyond binary scales
4. Discussion
Orbital motion and eccentricity

- **Orbit** causes a strong Coriolis shock in the pulsar wind and more instability.
- A spiral structure forms (orbital plane; expanding perpendicularly).
- For high $e$ a mixed fast outflow is produced in the apastron direction.
- HMMQ jets also affected by orbit.

(Barkov & B-R 2021; see observations: e.g. Pavlov+2015)

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Large scale interactions

- Mass-loaded, reaccelerated fast outflow interacts with medium.
- Evidence of large scale radio, X-ray and gamma rays: local acceleration;
  (e.g. Mirabel+92; Safi-Harb+99; Paredes+07; HAWC; HESS)
- Adiabatic losses in expanding outflow prevent binary CR to reach the ISM.
- What is the role of proper motion? Bent jets? sPWN-like?

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Most relevant aspects?

- The stellar wind and orbital motion shape the HMGB relativistic outflows via shocks, turbulence, mixing...
- This leads to different regions likely to host non-thermal activity:
  - Efficient acceleration of $e^\pm$ and p/nuclei in the strongly dissipative outflow.
  - Dense radiation fields; fast synchrotron, IC and escape.
- On large scales:
  - Extended radio, X-rays and gamma rays are detected.
  - Adiabatic cooling implies efficient acceleration.
- Relativistic HMGB are young powerful (moving) systems that can significantly affect the ISM due to their large luminosity.
- Small galactic population (10s of sources?) with a non-trivial role in the high-energy sky (UHE $\gamma$-rays, PeV CR and... perhaps even $\nu$?).
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Thank you.
BACKUP SLIDES
LS 5039 at high energies

- O6.5V(f) + a possible neutron star at $\approx 2 \text{ kpc}$
- $P \approx 3.9\ \text{days}$ and $e \approx 0.35$
- Reaching $\approx 2 \times 10^{35}\ \text{(GeV)}$ and $5 \times 10^{33}\ \text{erg s}^{-1}\ \text{(TeV)}$.
- MeV detection (consistent variability and SED) reaching $\approx 5 \times 10^{35}\ \text{erg s}^{-1}$.

(Casares et al. 2005a; Aharonian et al. 2006; Takahashi et al. 2009; Chang et al. 2016; Yoneda et al. 2021)
Moderately eccentric, compact, O+CO? binary

Detected by HAWC up to $\sim 100$ TeV.

(HESS: Bordas et al. 2015; Goodman, Gamma2022)
1FGL J1018.6−5856 at high energies

- O6V(f) + a possible neutron star at $\approx 6.4$ kpc
- $P \approx 16.6$ days and $e \approx 0.53$
- Reaching $\approx 10^{36}$ (HE) and $5 \times 10^{33}$ erg s$^{-1}$ (VHE)
- Possibly detected in MeV

(Ackermann et al. 2012; HESS 2015; Collmar, VGGRS 2017; van Soelen et al. 2022)
1FGL J1018.6−5856 > 10 TeV

Moderately eccentric?, relatively compact, O+CO? binary (10s)

Fig. 1. SED of HESS J1018−589 A/1FGL J1018.6−5856 is shown in black (filled squares and circles for the LAT and HESS detection). For comparison, the SEDs of LS 5039 during superior (SUPC) and inferior conjunction (INFC) are also included (blue points from Hadasch et al. 2012; Aharonian et al. 2005a).
LCM P3 at high energies

- O5III(f) + a possible neutron star at $\approx 50$ kpc
- $P \approx 10.3$ days and $e \approx 0.4$
- Reaching $\approx 4 \times 10^{36}$ (HE) and $5 \times 10^{35}$ erg s$^{-1}$ (VHE)

(Corbet et al. 2016; HESS 2018; van Soelen et al. 2019)
Moderately eccentric, compact, O+CO? binary

**Fig. 3.** Spectral energy distribution averaged over the full orbit (green, squares) and for the on-peak orbital phase range (orbital phase from 0.2 to 0.4: blue, circles). The data points have 1σ statistical error bars, upper limits are for a 95% confidence level. The best fit and its uncertainty are represented by the solid lines and shaded areas, respectively.
**LS I +61 303 at high energies**

- B0V(e) + a neutron star at \( \approx 2 \text{ kpc} \)
- \( P \approx 26.5 \text{ days} \) and \( e \approx 0.6 - 0.7 \)
- Reaching \( \approx 2 \times 10^{35} \text{ (HE)} \) and \( 5 \times 10^{33} \text{ erg s}^{-1} \text{ (VHE)} \)
- Similar MeV SED to LS 5039

(Casares+2005b; Albert+2006; Zhang+2010; Hadasch+2012; Collmar, VGGRS 2017; Weng+22)

Messy behavior due to superorbital modulation.
Eccentric, relatively compact, Be+ pulsar binary

Figure 3: Spectral energy distribution (SED) for LS I +61°303 for two parts of the orbit (parts of the orbit shown on top panels). SED on the left is for apastron passage covering $\phi = 0.5 \rightarrow 0.8$ and SED on the right is for the rest of the orbit for $\phi = 0.8 \rightarrow 0.5$. The orbital parameters shown on top panel are used from [14]

(VERITAS: Kar et al. 2017)
HESS J0632+057 at high energies

- B0V(pe) + a possible neutron star at \( \approx 2 \text{ kpc} \)
- \( P \approx 317 \text{ days} \) and \( e \approx 0.6 - 0.8 \)
- Reaching \( \approx 10^{34} \) (HE) and \( 3 \times 10^{32} \text{ erg s}^{-1} \) (VHE)

(Casares et al. 2012; Li et al. 2017; Moritani et al. 2018; Adams et al. 2021)