γ-loud binaries
(γ-ray emitting binaries)

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High-Energy Phenomena in Relativistic Outflows VI

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Outline

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1. Introduction
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3. Physics of $\gamma$-loud binaries
• **γ-loud binaries** are among the most luminous galactic sources.
• These binaries host stars and usually compact objects.
• These sources have often been characterized using analogies with AGN jets or PWN.
• Only recently, models have gone beyond the analogy paradigm, e.g. including orbital motion, uncovering specific physics.

Classes of $\gamma$-loud binaries

Subclasses: massive star binaries, WD+RG novae, binaries with pulsar, microquasars...

Pshirkov 2016; Zanin et al. 2016)
Classes of $\gamma$-loud binaries (II)

- **High-mass microquasars** host a compact object (BH/NS), which produces relativistic jets that interact with the stellar wind.
- Binaries **hosting a non-accreting pulsar** present relativistic pulsar-star/wind interactions.
- Binaries hosting **two massive stars** with interacting winds.
- **Symbiotic and classical novae** produce ejecta that can fuel $\gamma$-ray emission.
- Five $\gamma$-loud binaries host compact objects of unknown nature.

(e.g. B-R & Khangulyan 2009; Dubus 2013)
The global emitting flow evolution is determined by:
- Supersonic winds/relativistic outflows
- Orbital motion
- Role of magnetic fields? beyond (ideal) MHD physics?

Many regions of energy dissipation have been identified on small, middle and large scales:
- Particles can be accelerated
- Synchrotron and inverse Compton are likely dominant and compete for the energy
- Competing/combining emitting sites?

Regarding non-thermal processes, in some sources
- particle acceleration should be very efficient
- gamma-ray emission should be very efficient
- gamma-ray reprocessing may actually be a minor factor?
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Novae

- The explosion of symbiotic and classical novae produce GeV $\gamma$-rays.
- Symbiotic novae harbour a red giant with a dense wind.
- Classical novae harbour a less evolved star.
- The low ejecta velocity may not be enough to produce TeV photons.
- Stellar wind/ejecta shocks, or ejecta internal shocks, may be the source of $\gamma$-rays.

(e.g. Martin & Dubus 2013; Chomiuk et al. 2014; Metzger et al. 2015; Cheung et al. 2016; Finzell et al. 2017)

Discovery: Fermi 2010

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- **Eta Car** is the only confirmed gamma-ray emitting massive star binary due to strong evidence of orbital variability (e.g. Reitberger et al. 2015).
- **WR 11** (\(\gamma^2\)-Velorum) is a possible nearby Fermi source (Pshirkov 2016; Benaglia 2016).
- Many massive star binaries are non-thermal radio emitters (de Becker & Raucq 2013; de Becker et al. 2017).
- Neither Eta Car nor WR 11 are non-thermal radio emitters, likely due to free-free absorption/TR effect.

(Modeling: e.g. Eichler & Usov 1993; Benaglia & Romero 2003; Reimer et al. 2006; Pittard & Dougherty 2006; Bednarek & Pabich 2011; Reitberger et al. 2014a,b; Ohm et al. 2015; del Palacio et al. 2016)
Massive star binaries (II)

GeV spectra of Eta-Car (Reitberger et al. 2015)

GeV TS map of WR 11 (Pshirkov 2015; see also Benaglia 2015)

Modelled Eta-Car lightcurve (Ohm et al. 2015)

Predicted youngest binary SED: HD 93129A (del Palacio et al. 2016)

See also, e.g., Reitberger et al. (2014a,b)

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Microquasars

- Both sources have powerful jets and heavy mass loss, $10 \times$ higher in Cyg X-3 (also $100 \times$ brighter).
- Cyg X-3 and Cyg X-1 emit GeV when the jet is present.
- The GeV emission is consistent with stellar IC scattering.
- MAGIC+07 detected Cyg X-1 in VHE at $4.1 \sigma$ post trial, $\sim$SUPC.
- AGILE+16 detected GeV photons from low-mass MQ V404 Cyg in outburst.

PSR B1259–63 is the only confirmed gamma-ray emitting high-mass binary hosting a young pulsar (e.g. Johnston et al. 1992, Aharonian et al. 2005; see also the candidate PSR J2032+4127; e.g. Lyne et al. 2015).

The star is a late O with a circumstellar disc (e.g. Negueruela et al. 2011).

The source presents non-thermal emission from radio to gamma rays several months/weeks before and after periastron passage, with evidence of disc crossing (e.g. Chernyakova et al. 2015, Xing et al. 2015).

It shows extended/moving X-ray features (e.g. Pavlov et al. 2015).

Pulsar binaries: PSR B1259−63 (II)

X-/gamma-ray lightcurves
(HESS 2015)

MW lightcurve (Chernyakova et al. 2015)

Periastron VLBI radio morphology (Moldón et al. 2011)
**γ-loud binaries of unknown nature (I)**

- **LS I +61 303 (Be)** is significantly more eccentric than **LS 5039** (O6) (e.g. Casares et al. 2005a,b) and similar (but more irregular) in NT behavior, being both extremely bright (e.g. Hadasch et al. 2012; Collmar & Zhang 2014; HESS 2015; MAGIC 2016; Saha et al. 2016; Zhang et al. 2016).

- **HESS J0632+057 (Be)** and **1FGL J1018.6−5856** (O6) (Hinton et al. 2009, Fermi 2012) also present a complex, not too dissimilar behavior to the other two (e.g. VERITAS 2015, HESS 2015).

- One has recently detected a source in **LMC** (O5) (Corbet et al. 2016; HESS 2017) and the candidates HESS J1832-093 (Eger et al. 2016) and MWC148 (Casares et al. 2014).

- Several of them show extended X-ray emission (e.g. Paredes et al. 2007; Durant et al. 2011; Williams et al. 2015).

(Modeling: e.g. Leahy 2004; B-R & Paredes 2004; Romero et al. 2005; Paredes et al. 2006; B-R et al. 2006; Dermer & Böttcher 2006; Aharonian et al. 2006; Bednarek 2006; Dubus 2006; Khangulyan et al. 2008; Dubus 2008; Sierpowska-Bartosik & Torres 2008; Takahashi et al. 2009; Cerutti et al. 2010; Zdziarski et al. 2010; Zabalza et al. 2011; Zabalza et al. 2013; Dubus et al. 2015; del Palacio et al. 2016)
Sources of unknown nature (II)

- LS 5039 (Takahashi et al. 2009)
- LS I +61 303 (Hadasch et al. 2012)
- LMC binary (Corbet et al. 2016)
- 1FGL J1018.6−5856 (HESS 2015)
- HEβ J0632+0577(VERITAS/HESS14)
- V. Bosch-Ramon (ICCUB)
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Binary scales: microquasar

- Jet strong, asymmetric recollimation shocks and fast instability growth are expected.
- Weak jets can even be disrupted within the binary system.

Presence of clumps strongly enhances the disruptive power of the wind.

(clumpy winds in massive stars: e.g. Moffat et al. 2008)

(Perucho & B-R 2008, 2012; Perucho et al. 2010; and see also Yoon & Heinz 2015 and Yoon et al. 2016)
The winds are shocked and then reaccelerate.

Adiabatic evolution reduces the pulsar wind magnetic field impact.

The interaction structure is prone to instabilities.

Large clumps strongly modify the interaction structure.

Even small clumps enhance instability growth.

(de la Cita et al. 2017)

(e.g. Bogovalov et al. 2008, 2012; Lamberts et al. 2013; Paredes-Fortuny et al. 2015; Dubus et al. 2015)
Non-ballistic flows: microquasar

- Microquasar jets cross the wind of the star while orbiting it.
- For $\chi = \frac{\theta_j \dot{P}_w}{4\pi \dot{P}_j} > 1$, the jets will be significantly affected by orbital motion.

The jet, surrounded and likely mass-loaded by shocked wind, develops an (unstable) spiral-like structure.

(B-R & Barkov 2016)
Non-ballistic flows: pulsar binary

2D and 3D simulations with orbital motion yield robust results.

(B-R et al. 2012, 2015)
Large scales: microquasar

- MQ jets deliver mechanical energy at their termination.
- MQ jets could face complex environments.

- The interaction with the medium can accelerate particles and produce high-energy radiation.

(B-R et al. 2011; see also Bordas+09, Yoon+11)

(Bordas+15)

(see also Gallo et al. 2005, Tudose et al. 2007, etc.)
Large scales: pulsar binary

Elliptic orbits lead to different morphologies wrt circular ones, showing strong outflows in the apastron direction and phase.

(Sharapov & Barkov 2011)

Shocked wind/ISM interaction.

(Barkov & B-R 2016)
Particle acceleration

- Stellar luminosity, system scales, and outflow velocities set constraints on particle acceleration.
- Different acceleration mechanisms may operate through strong shocks, turbulence, shear layer, magnetic field...
- Accelerated rates $\dot{E} \sim 0.01 - 0.1 \ q B c$ should be reached in some $\gamma$-loud binaries.

(e.g. Takahashi et al. 2009; Zabalza et al. 2011, 2013; B-R & Rieger 2012)

Leptonic scenario; LS 5039 (Khangulyan et al. 2008)
Radiation reprocessing

- Pair creation above $10 - 100$ GeV on stellar photons is in principle expected in compact systems.
- Absorption + synchrotron (high $B$) $\rightarrow$ high X-rays.
- Absorption + IC (low $B$) $\rightarrow$ high GeV.
- Typically, the compact sources do not present clear features of absorption or cascading.
- Therefore, the emitters are likely in the system periphery.

(e.g. Bednarek & Giovanelli 2007; B-R et al. 2008; Zdziarski et al. 2009; Cerutti et al. 2010)