High-Energy Processes in Gamma-Ray Binaries

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Outline

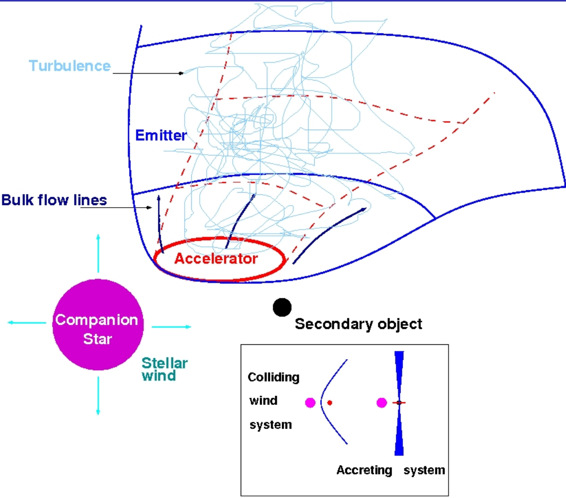
1. Introduction
2. The properties of the non-thermal emission
3. Flow dynamics
4. High-energy radiation reprocessing
5. Radiation/dynamics coupling

Outline

Gamma-ray binaries

- Study of particle acceleration and emission processes in compact, extreme, variable/periodic conditions.
- Good combination of environment, geometry, size and timescales to study high-energy processes common to SNR, PWN, AGN, GRB...
- Multi-scale processes: from $\sim 10^7$ cm to $\sim$ pc
- Link with massive stars

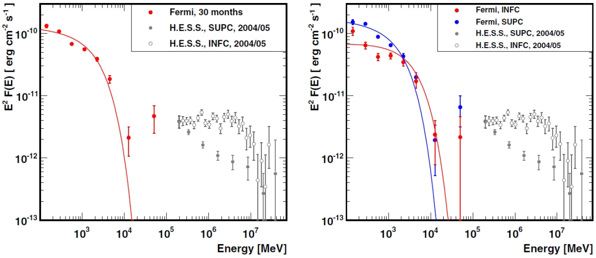
(see also Araudo's and Romero's talks)

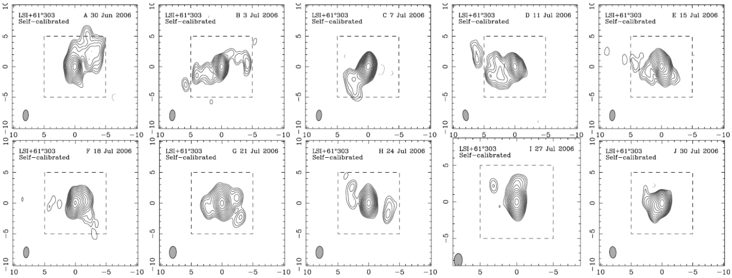


Subclasses: binaries with pulsar, microquasars, massive star binaries, WD+RG novae, and unclear objects...

THIS TALK: no pulsars (previous section) nor accretion (Inoue's talk?)

Data start to allow the study of more detailed physics behind radiation





(e.g. Hadasch et al. 2012; Aharonian et al. 2006; Massi et al. 2012; see also, e.g., Dhawan et al. 2006, Moldón et al. 2012)

(see also Meier's and Sushch's talks)

Preliminary remarks

1. **Gamma-ray binaries are heterogeneous both population-wise and physically, although share basic processes (acceleration, radiation, reprocessing).**
2. From the phenomenological point of view, the massive star and the orbit can play a dominant role.
3. Accretion vs colliding winds is a fundamental difference in the energy source, although higher layers of phenomena can mask it.
4. A proper study requires:
   - High resolution in radio (structure), and sensitive observations in GeV and TeV (processes and structure) simultaneously with X-rays (processes, structure)
   - Spectroscopy (accretion, wind, orbit, CO nature...), astrometry (system origin...), timing analysis (pulsations, accretion...)
   - and MHD and advanced radiation modeling

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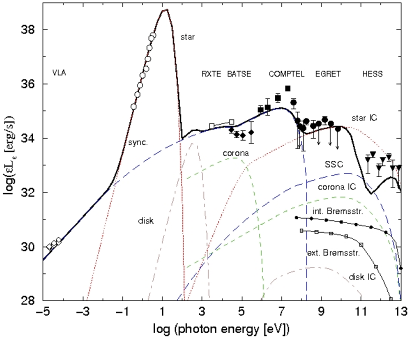
Outline

Broadband emission

- Leptonic: synchrotron (radio - X-rays) and inverse Compton (gamma rays)
- Hadronic: *pp*, $p\gamma$, photodisintegration, *p*-synchrotron
  pp / $p\gamma$ - $e^{\pm}$ $\rightarrow$ leptonic emission.
- Radiation absorption, $e^{\pm}$ creation and reemission can be important.



(Paredes, Romero & B-R 2006)

(see also, e.g., Aharonian et al., Bednarek et al., B-R et al., Dermer&Boettcher et al., Dubus et al., Khangulyan et al., Neronov&Chernyakova et al., Romero et al., Torres et al., etc.)

The accelerator: maximum energies

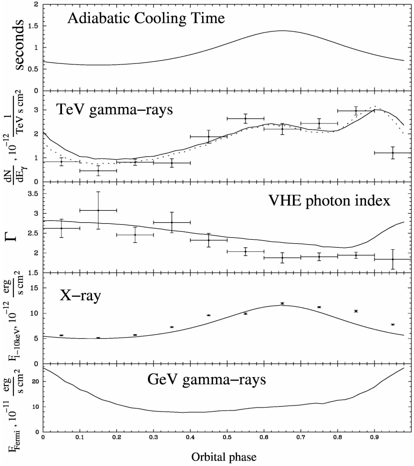
- Rate balance ($t_{\rm acc} = \eta\, E/q\,B\,c = t_{\rm cool}$; $\eta \geq 1$) yields
  - Synchrotron: $E_{\rm max}^{\rm sy} = 60\,\eta^{-1/2}\,B_{\rm G}^{-1/2}$ TeV
  - KN IC: $E_{\rm max}^{\rm KN} \sim 10^{10}\,(B_{\rm G}\,T_{\rm UV}^{1.7}\,u_{100}^{-1}\,\eta^{-1})^{3.3}$ TeV
    (Th. IC: $E_{\rm max}^{\rm Th} = 2500\,B_{\rm G}^{1/2}\,u_{100}^{-1/2}\,\eta^{-1/2}$ GeV)
  - "Dynamical" time: $E_{\rm max}^{\rm dy} \sim 910\,R_{12}\,B_{\rm G}\,v_{10}^{-1}\,\eta^{-1}$ TeV
  - Diffusion: $E_{\rm max}^{\rm diff} = 370\,R_{12}\,B_{\rm G}\,\eta^{-1/2}\,\chi^{-1/2}$ TeV
- Electrons are strongly affected by synchrotron cooling, but adiabatic cooling and escape cannot be neglected. Protons are most likely affected by adiabatic losses or escape.

The mechanism does not need to be one nor the same in all sources.

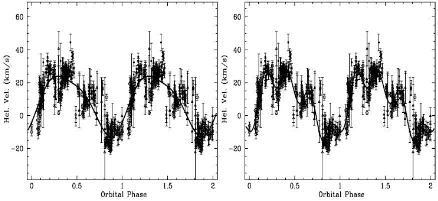
(see, e.g., Rieger, B-R & Duffy 2007; Khangulyan, Aharonian & B-R 2008; B-R & Rieger 2011; see also Derishev's talk)

Variability ("extrinsic")

- The orbit induces variability through environment, target and geometry changes, and triggering flow instabilities.
- Inhomogeneities in the stellar wind can generate short time variability.
- Additional modulation on short/long timescales: stellar variations, accretion disc/jet precession...



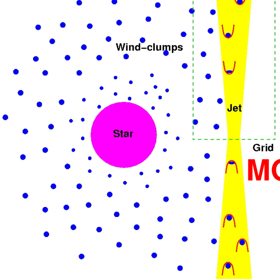
(Takahashi et al. 2009)

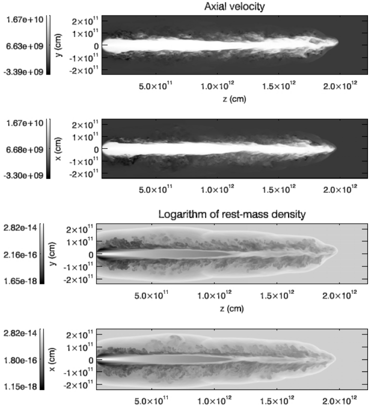


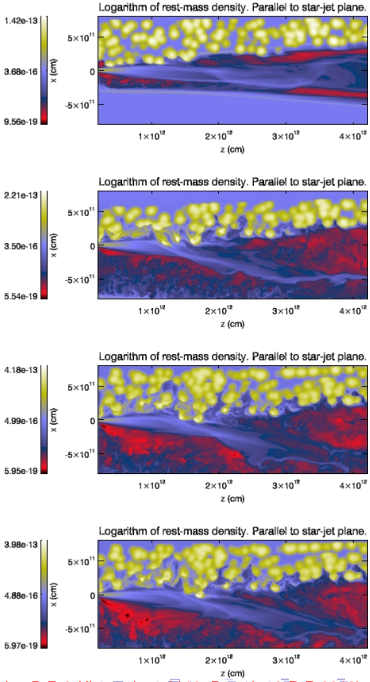
(Casares et al. 2011)

Outline

MQ Jets

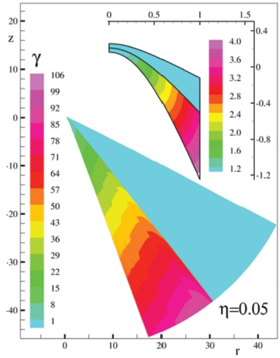


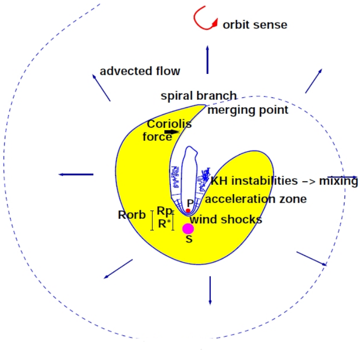


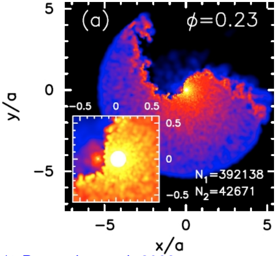


(Perucho, B-R & Khangulyan 2010; Perucho & B-R 2012)

Colliding winds

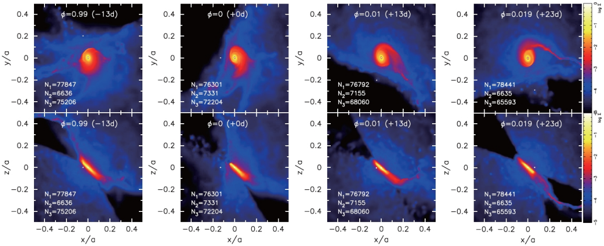






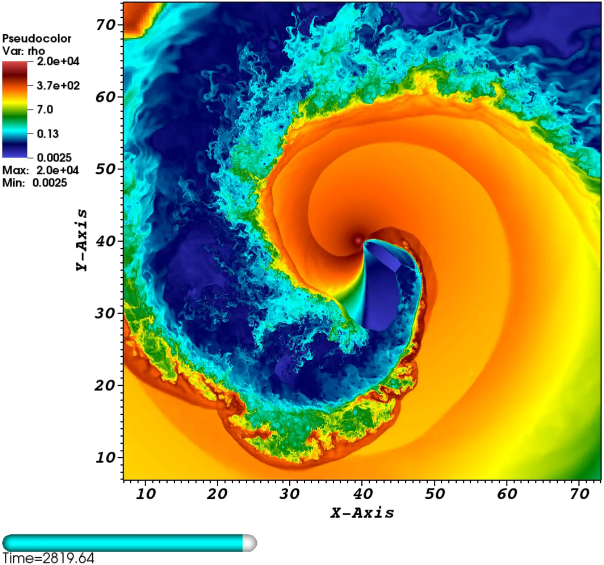
(↑ Bogovalov et al. 2008;

↓ Romero et al. 2007)



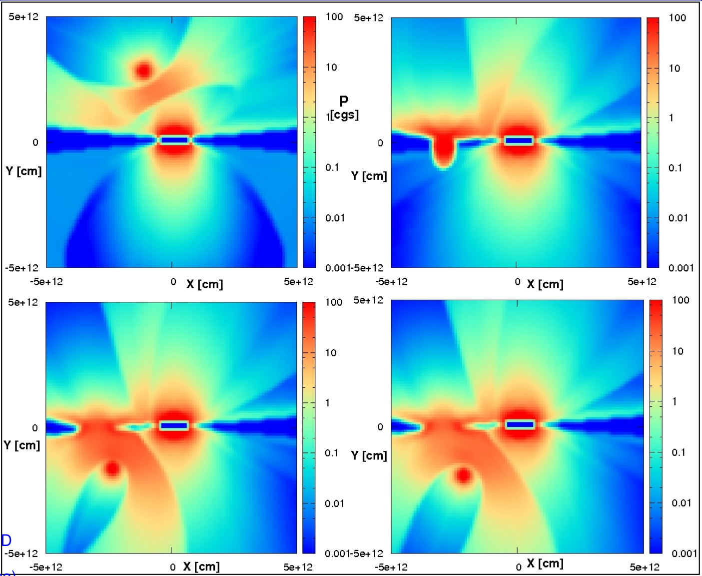
(↑ B-R & Barkov 2011; ↓ Okazaki et al. 2011)

Colliding winds



(B-R, Barkov, Khangulyan & Perucho 2012)

Role of the disc in Be+pulsar binaries

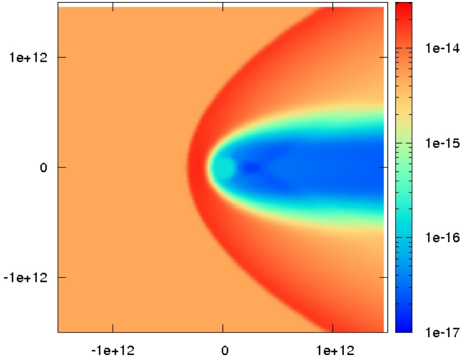


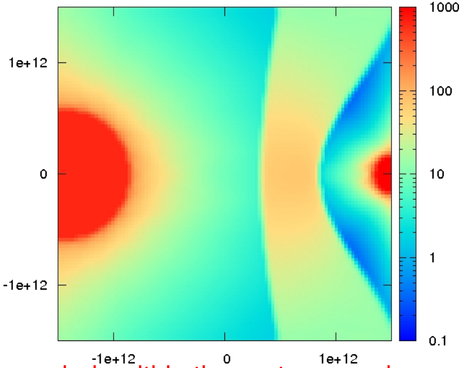
(HLLE Newt. 3D
2nd order space)

(see also Okazaki et al. 2011; for the disc impact on the GeV radiation, see **Khangulyan et al. 2012** ; see also van Soelen's talk.)

Binary environment impact

The outflows affect the stellar wind within the binary with likely impact in the radio emission (ionization degree), X-rays (thermal radiation, voids), optical (lines)... (e.g. Zabalza, B-R, & Paredes 2011; Szostek et al. 2012) (2D: Marquina, Newtonian/HLLE, rel.)



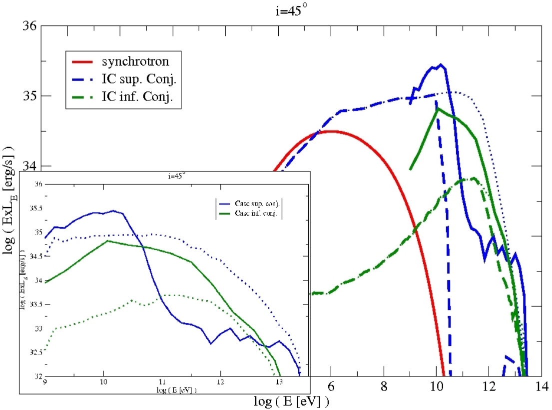


The solid angle covered by jets and pulsar winds within the system may be similar, despite of the strong difference in energy flux anistropy.

Outline

Inverse Compton cascading

- Full IC cascading computed consistently with a one-zone IC model (low *B*).
- The system is more transparent at INFC at $\epsilon_\gamma \gtrsim$ 100 GeV, but less at $\epsilon_\gamma \lesssim$ 100 GeV.
- The size of the gamma-ray emitter may not be negligible (*B*?).



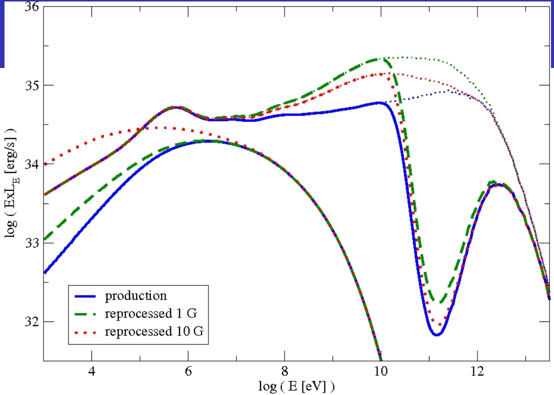
Preliminary

(see, also, Bednarek 2000; Aharonian et al. 2006; Orellana et al. 2007; Khangulyan et al. 2008; Sierpowska-Bartosik & Torres 2008; Cerutti et al. 2010...)

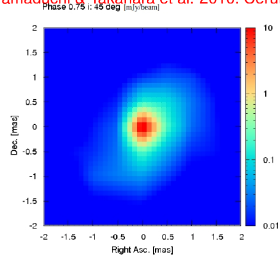
Secondary $e^{\pm}$ synchr.

- Simplified (isotropic) 3D cascade accounting for $e^{\pm}$ synchrotron.
- In binary systems, $B_{\rm w} \sim$ few G are enough to suppress the cascade.
- $e^{\pm}$ synchrotron and IC emission constrains deabsorption of TeV spectra/location of the emitter.
- Impact in radio $\rightarrow$

(see B-R & Khangulyan 2011)



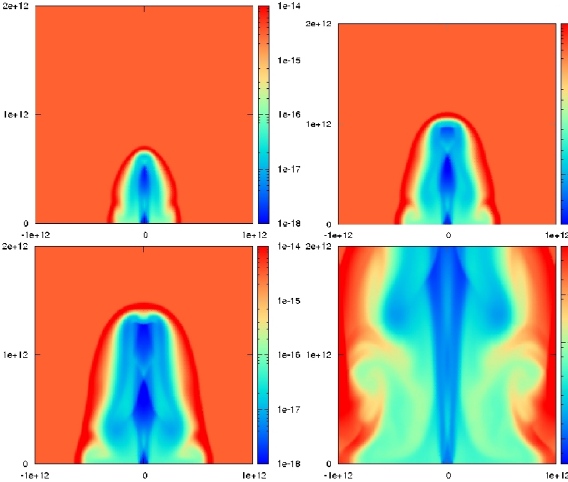
Preliminary (see, also, Khangulyan, Aharonian & B-R, B-R, Khangulyan & Aharonian 2008, Yamaguchi & Takahara et al. 2010. Cerutti et al. 2010...)



Outline

A transient jet (I)

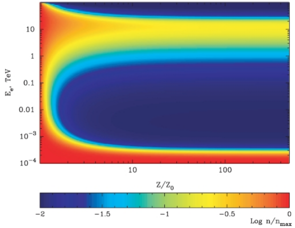
- $L_{\rm jet} \sim 10^{37}$ erg/s and $\Gamma_{\rm j0} \approx 5$; O star wind $a \sim 3 \times 10^{12}$ cm.
- Recollimation and termination shocks form quickly, with dissipation efficiencies $\gtrsim 10\%$.
- The real structure will be asymmetric because of the stellar wind.



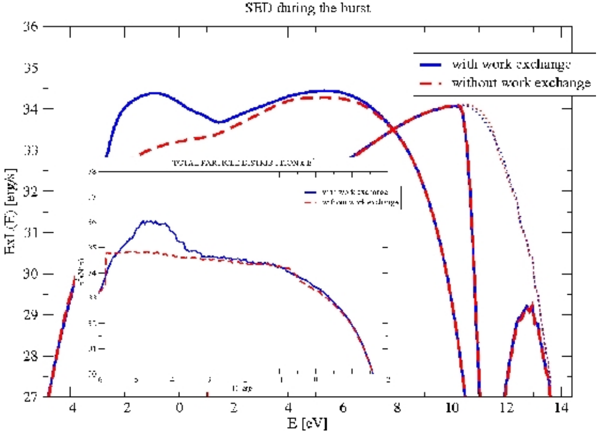
2D RHD (2nd order in space; HLLE Riemann solver)

A transient jet (II)

- Similar to a one zone model, but...
- work exchange is important,
- and propagation can strongly impact absorption.



(Khangulyan, Aharonian & B-R 2008)

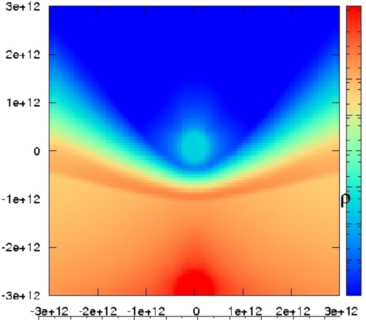


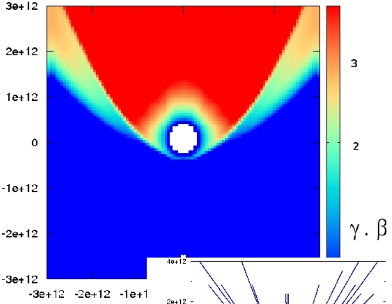
Preliminary (see also Khangulyan, B-R & Perucho, in prep.)

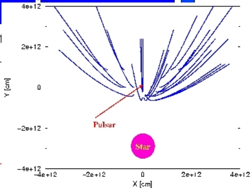
Recent semi-analytic work:

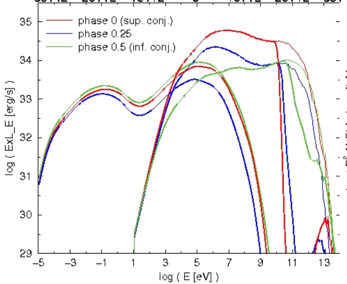
e.g. Araudo et al. (clump/jet), Bordas et al. (jet termination)

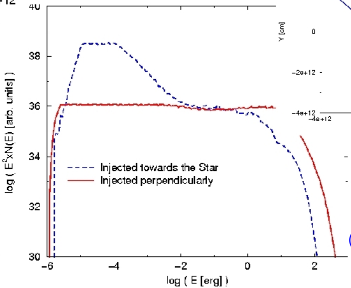
Colliding winds: Particles injected in the pulsar wind shock follow the fluid lines. Adiabatic heating also important?











Preliminary (HLLE 2D, rel.)

(see also Takata et al. 2012;

Bogovalov's talk)