High-energy gamma-ray emission in compact binaries

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PhD defense, June 10th 2010, Grenoble
1. **Binary systems** in the gamma-ray sky!
2. High-energy **processes** & **anisotropies**
3. **Gamma-ray** emission in gamma-ray binaries
4. **Pair cascade** emission in gamma-ray binaries
5. Gamma-ray emission from **relativistic outflow**
6. Conclusions & futures directions
Binary systems in the gamma-ray sky!
Gamma rays

Electromagnetic spectrum:

- High-energy (HE): \( \sim \text{GeV} \ (10^9 \text{ eV}) \)
- Very-high energy (VHE): \( \sim \text{TeV} \ (10^{12} \text{ eV}) \)

Gamma ray: photon \( > 511 \text{ keV} \)
Gamma-ray Astronomy

Gamma-ray telescopes

From space: GeV domain

Fermi, AGILE

anticoincidence shield
conversion foil
particle tracking detectors
calorimeter

From the ground: TeV domain

HESS, MAGIC & VERITAS

Simultaneous coverage of HE and VHE domains
Unprecedented sensitivity and angular resolution

γ-ray astronomy!

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The gamma-ray sky

1 year of exposure

Extra-Galactic $\gamma$-ray sources:
- Active Galactic Nuclei (AGN)
- Gamma-Ray Bursts (GRB)
- Starbursts Galaxies

Galactic $\gamma$-ray sources:
- Pulsars & Pulsar wind nebulae
- Supernovae remnants
- Many are unidentified
- ... and 4 binary systems!
Gamma-ray emitting binaries

1 year of exposure

(Cyg X-1?)
LS I +61°303
Cyg X-3
LS 5039
PSR B1259-63
(HESS J0632+057?)

2 kpc
7 kpc
2.5 kpc
1.5 kpc

Credit: NASA/DOE/Fermi LAT Collaboration

Legend

Massive star
Compact object orbit

26.5 days
4.8 hours
3.9 days
1240 days

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Two classes of binaries

**GAMMA-RAY BINARIES**

Massive star + young pulsar

[Maraschi & Treves 1980, Dubus 2006b]

**MICROQUASAR**

Massive star + accreting compact object (neutron star or black hole)

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**ROTATION-POWERED**

LS I +61°303, LS 5039 & **PSR B1259-63**

(HESS J0632+057?)

**ACCRETION-POWERED**

Cyg X-3 (Cyg X-1?)

Credit: F. Mirabel
Why are these systems so interesting?

**Gamma-ray binaries**
- Nearby systems (kpc) and well constrained physical conditions (stellar radiation field, orbit)
- Probe relativistic winds at small scale: 0.1 AU!
- Exploration of new class of Galactic objects (population, evolution)
- Application to pulsars and PWN

**Microquasars**
- Nearby systems (kpc) and well constrained physical conditions (stellar radiation field, orbit)
- Study the physics of relativistic jets, accretion-ejection mechanisms at small scales (AU-pc)
- Application to e.g. AGN & GRBs

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[Credit: F. Seward et al, J. Hester & A. Loll, R. Gehrz]
Gamma-ray beacons: the case of **LS 5039**

- GeV/TeV stable orbital modulation
- Min/Max at **conjunctions**
- Geometrical effects ?!

**Credit: M. de Naurois**

**Conj. Sup.  Conj. Inf.**

[Aharonian et al. 2006]
What we want to understand

GeV and/or TeV orbital modulation

**GeV**
- LS I +61°303 [Fermi LAT, 2009a]
- LS 5039 [Fermi LAT, 2009b]
- Cygnus X-3 [Fermi LAT, 2009c]
- (PSR B1259-63 ?)

**TeV**
- LS I +61°303 [MAGIC coll., 2008]
- LS 5039 [HESS coll., 2006]
- PSR B1259-63 [HESS coll., 2005]

**Key questions**
- Where does the gamma-ray modulation come from?
- What are the relevant processes in binaries? Acceleration site?
- What can we learn on pulsar winds and relativistic jets?

**Goal thesis ➔** Theoretical modeling of temporal & spectral γ-ray variability
High-energy processes & anisotropies
Relevant high-energy processes

**Leptonic**
- Inverse Compton scattering
- Synchrotron radiation
- Triplet Pair Production

**Hadronic**
- Proton-proton collision
- Photomeson production

**Absorption**
- Pair production
Anisotropies

- High UV stellar photon density, **dominant source** ($n_{ph} \approx 10^{14}$ ph/cm$^3$ in LS 5039!)
- **Anisotropic** and **well constrained** radiation source
- **Angular dependence** on:
  - inverse Compton scattering (**emission**) & **pair production** (**absorption**)
Anisotropic inverse Compton scattering

Derivation of **new analytical formulae** for anisotropic inverse Compton scattering

Circular orbit with an inclination $i=90^\circ$

Massive star: **Black-body** spectrum

Relativistic electrons with a -2 **power-law**

- **Head-on:** $e^\pm \rightarrow \gamma$ (Max)
- **Rear-end:** $e^\pm \rightarrow \gamma$ (Min)

Observer!

$\psi=180^\circ$

$\psi=30^\circ$

Fermi

ACT

Strong angular dependence!

Similar dependence for **pair production**
Gamma-ray emission in $\gamma$-ray binaries
The scenario: the big picture!

[Maraschi & Treves 1981; Dubus 2006b]

Classical pulsar wind model

[Rees & Gunn 1974, Kennel & Coroniti 1984]

- "Unshocked": cold plasma of relativistic e\(^+\)/e\(^-\) pairs: \(v_w \approx c\)
- "Shock": pairs randomized and reaccelerated: \(v_w \approx c/3\)
- Model applied to PSR B1259-63

[Tavani et al. 1994, Kirk et al. 1999, Ball & Kirk 2000, Khangulyan et al. 2007]
Emission from the “shocked” wind

[Maraschi & Treves 1981; Dubus 2006b]

Assumptions

- **Isotropized** pairs with power-law
- **Anisotropic inverse** Compton with stellar photons
  + Synchrotron
  + **Anisotropic** pair production

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Application to LS 5039

High inclination favored
compact object = pulsar
GeV/TeV anti-correlation predicted! (due to absorption)
[see also Bednarek 2006, Khangulyan et. al 2008]

[Dubus, Cerutti & Henri, A&A 2008]
Strength & weakness

Strength

- **Simple** model
- Explains most of the GeV and TeV modulation in LS 5039.
- **Robust constraints** on physical parameters (B, p, L_p)

Weakness

- **Fermi** observations **not explained**!
  Extra-component required.
- **HESS** flux @ superior conjunction **not explained** in LS 5039 ➔ **Pair Cascades**?
- Modulation in LS I +61°303 and PSR B1259-63 **not explained**
Emission from the “unshocked” pulsar wind

[Maraschi & Treves 1981; Dubus 2006b]

Observer!

Assumptions

- Mono-energetic pulsar wind: Lorenz factor $\gamma_0$
- Inverse Compton with stellar photons, no synchrotron
- Kinetic energy dominated wind ($\sigma << 1$)
Application to $\gamma$-ray binaries

- **LS 5039**
  - $\gamma_0 = 10^4$
  - $10^5$
  - $10^6$
  - $10^7$

- **LS I +61° 303**
  - $10^8$
  - $10^9$
  - $10^{10}$
  - $10^{11}$

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- **Strong** line-like spectra! $\Rightarrow$ **Excluded** by Fermi and TeV observations
- **Not mono-energetic**, e.g. power-law? [Sierpowska-Bartosik & Torres 2008]
- Conversion **Electromagnetic** to kinetic energy **not completed**? Striped wind?

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[Cerutti, Dubus, & Henri, A&A 2008]

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- $R_s \approx 0.1$ d
- No shock

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Pair cascade emission in $\gamma$-ray binaries
Motivations

- **Model:** Huge absorption at superior conjunction ➔ no TeV flux…
- ...but, excess measured by HESS!

**Solution:** Pair cascade emission!

- Absorbed energy **recycled** ➔ Emission of new generations of pairs
- **Increase the transparency** of the source at superior conjunction.

[Dubus, Cerutti & Henri, A&A 2008]
The physics of pair cascading

Ambient magnetic field

Primary $\gamma$-ray

Stellar photon

1st generation

2nd generation

etc. ...
Cascade regimes

- Magnetic deviations negligible ($B < 10^{-8} \text{ G}$)
- Pairs and photons boosted in the direction of primary $\gamma$-rays

- Pairs locally isotropized ($R_L < \lambda_{IC}$)
- Extended & anisotropic emission

- Dominant Synchrotron cooling ($t_{\text{syn}} < t_{ic}$)
- X-ray emission, $\gamma$-ray emission quenched
1D cascade

- **No magnetic field** (or $B < 10^{-8}$ Gauss)
- Cascade develops **along the line of sight** $\Rightarrow$ **High anisotropy**
- **Complete** and **accurate** semi-analytical calculation possible (all generations)

**Ex: LS 5039 at sup. conj.**
Application to LS 5039

\[ \text{[Cerutti, Dubus & Henri, A&A 2009]} \]

- Contribution too high from the cascade
  \[ \Rightarrow \text{Cascade 1D excluded!} \]

- Upper limit for the cascade contribution @ superior conjunction
  \[ \Rightarrow \text{Cascade 3D not excluded} \]
Cascade regimes

- Magnetic deviations negligible (B<10⁻⁸ G)
- Pairs and photons boosted in the direction of primary γ-rays

<table>
<thead>
<tr>
<th>10⁻⁸ G</th>
<th>10⁻² G</th>
<th>10 G</th>
</tr>
</thead>
<tbody>
<tr>
<td>1D Cascade</td>
<td>3D “isotropic” Cascade</td>
<td>Quenched 3D Cascade</td>
</tr>
</tbody>
</table>

- Pairs locally isotropized (R_L < λ_IC)
- Extended & anisotropic emission
- Dominant Synchrotron cooling (t_syn < t_ic)
- X-ray emission, γ-ray emission quenched
3D cascades: assumptions

- Pairs **isotropized** at creation
- Compton & synchrotron **radiation** and **cooling**
- **No explicit** full analytical calculation possible

→ **Decomposition** into **discrete generations** of particles

- **Methods:**
  1. Semi-analytical (1\textsuperscript{st} generation)
  2. Monte Carlo (all generations)
→ **Collaboration with Julien Malzac**

Both methods **compatible**

Effect of **extra-generations** important

\[
\begin{align*}
@ 1 \text{ TeV} & \Rightarrow 10^{-2} \text{ G} < B < 5 \text{ G}
\end{align*}
\]

[Cerutti, Malzac, Dubus, & Henri, A&A 2010, (accepted)]
Spatial distribution $1^{\text{st}}$ generation $\gamma$ rays

Application to LS 5039: Semi-analytical results

Normalized gamma-ray density (ph s$^{-1}$ cm$^{-3}$, > 1 TeV)

$\psi=30^\circ$

$\psi=150^\circ$

[Cerutti, Malzac, Dubus, & Henri, A&A 2010, (accepted)]
3D cascade modulation in LS 5039

Fermi

HESS

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3D cascade modulation in LS 5039

\[ i = 40^\circ \]

- **Total**
- **3D Cascade only**

More flux @ sup. Conjunction!

[Cerutti, Malzac, Dubus, & Henri, A&A 2010, (accepted)]

- Rather low inclination: \( i \approx 40^\circ \)
- TeV source should lie close to the compact object
- Ambient magnetic field \( B < 10 \text{ G} \) (synchrotron radiation from pairs in the cascade)
γ-ray emission from relativistic outflow
The puzzling X-ray modulation in LS 5039!

**Suzaku observations**

X-rays

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**X-ray lightcurve**

- **Orbital modulation**
- **Min and Max at conjunctions:**
  - **Intrinsic** variation *unlikely*
  - **Geometrical** explanation

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Solution: Doppler Boost!

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[Takahashi et al. 2009]

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[Image of X-ray lightcurve with orbital phase and counts per second.]

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**Observer!**

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Massive star

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Flow

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Shocked wind

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Ψ
Boosted emission in LS 5039

- Shocked pulsar wind $\approx$ radial
  (stellar wind speed $>>$ orbital motion pulsar)

- Mildly relativistic wind $\beta = 1/3$ ($=v/c$)
  - TeV modulation $\approx$ unchanged
  - X-ray modulation $\approx$ reproduced

[B. Cerutti, PhD defense, June 10th 2010, Grenoble]
**Boosted emission in LS I +61°303 (1)**

- **Model:** Pulsar wind *trailing* in the Be Keplerian disk

- **Mildly relativistic wind β=1/3:**
  - X-ray and TeV both *correlated* and maximum close to apastron

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**Deboosted!**

**Boosted!**

\[ β=0 \quad \rightarrow \quad \text{Boost} \quad \rightarrow \quad β=1/3 \]

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**[Dubus, Cerutti, & Henri 2010b]**
Boosted emission in \textbf{LS I +61°303 (2)}

**MAGIC lightcurve**

\[
F(\text{E}=400 \text{ GeV}) \, [10^{-12} \text{ cm}^2 \text{s}^{-1}] = 2.45 \times 10^{-12} + 4.28 \times 10^{-12} \cdot e^{-0.04/0.005} + 1.35 \cdot \sin(2\pi \cdot (\theta + 0.51))
\]

\[
\chi^2/\text{NDF} = 58.1/13
\]

\[
F(\text{E}=100 \text{ GeV}) \, [10^{-12} \text{ cm}^2 \text{s}^{-1}] = 3.02 \times 10^{-12} + 2.35 \times 10^{-12} \cdot \sin(2\pi \cdot (\theta + 0.46))
\]

\[
\chi^2/\text{NDF} = 126.3/16
\]

[Albert et al. 2009]

**X-\gamma correlation**

[Andershub et al. 2009]

**Model for \( \beta = 1/3 \)**

\[ \beta = 1/3 \]

[Dubus, Cerutti, & Henri 2010b]

- The Boost in \textbf{LS I +61°303} could explain \textbf{TeV and X-ray modulations}!
- \textbf{Same model for PSR B1259-63}
  - \textbf{small impact}
Two classes of binaries

**GAMMA-RAY BINARIES**

Massive star + young pulsar  
*Maraschi & Treves 1980, Dubus 2006b*

**MICROQUASAR**

Massive star + accreting compact object  
(neutron star or black hole)

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**ROTATION-POWERED**

LS I +61°303, LS 5039 & **PSR B1259-63**  
(HESS J0632+057?)

**ACCRETION-POWERED**

Cyg X-3  
(Cyg X-1?)

Credit: F. Mirabel

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Cygnus X-3: The first GeV microquasar!

[Fermi LAT coll., 2009c]

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- **First firm detection** of a microquasar at GeV by AGILE & Fermi [Tavani et al. 2009, Fermi LAT coll. 2009c]
- γ-ray flares **correlated** with radio flares
  - γ-ray emission related to the jet
- γ-ray flux **modulated** at the orbital period (4.8 h)
Relativistic Doppler emission in **Cygnus X-3**

**Assumptions**
- **Boosted Inverse Compton** stellar photons – pairs in the jet
- The jet is **inclined & relativistic**
- Energetic electrons **located @ specific locations**

**Parameters**
- **5 free** parameters
- Exhaustive exploration of parameter space $\Rightarrow \min \chi^2$
Best fit solution

Constraints

- $e^\pm$ not located within the system
- Jet inclined close to the line of sight ($\mu$-blazar!)
- Jet mildly relativistic ($\beta < 0.9$)
- Black-hole favored
- Precession of the jet: strong impact on the modulation

[Dubus, Cerutti, & Henri, MNRAS 2010a]
Conclusions & futures directions
Summary

Pulsar wind emission

- **Shocked**: Anisotropic IC + absorption: TeV modulation OK in LS 5039.
- **Unshocked**: Strong emission excluded: wind highly magnetized?

Publications: [Dubus, Cerutti, & Henri, 2008]; [Cerutti, Dubus, & Henri 2008]

Cascades

- 1D cascade: provides an upper limit, excluded in LS 5039
- 3D cascades: Viable solution for TeV flux @ sup. conj. in LS 5039

Publications: [Cerutti, Dubus, & Henri, 2009]; [Cerutti, Malzac, Dubus, & Henri, 2010]

Boosted emission

- γ-ray binaries: changes significantly high-energy modulation (X, γ)
- Cygnus X-3: Boosted Compton scattering → GeV modulation OK

Publications: [Dubus, Cerutti, & Henri, 2010a]; [Dubus, Cerutti, & Henri, 2010b]
Open questions and looking forward

Open questions

- What is the origin of the GeV component? - Striped pulsar wind in binaries?
- What is the origin of the $\gamma$-ray modulation in LS I +61°303 and PSR B1259-63?
- Particle acceleration in microquasar jet?

Looking forward

- Present and future observational backdrop favorable (Fermi, CTA, ...)
  ➔ Discovery of new systems!
- Exciting new modeling challenges with GeV observations!
  (pulsar emission, model for microquasars...)
- Theoretical expertise in high-energy processes in astrophysics
  ➔ Application to many other objects e.g.:
  - AGN and GRBs
  - Pulsars, PWN... and magnetars!
Future directions

Post-doc

- **Research associate** position with Pr. Dmitri Uzdensky in Theoretical plasma astrophysics @ University of Colorado, Boulder, USA.

- Magnetic reconnection in **High-energy-density astrophysical environment (e.g. magnetars & GRBs)**

University of Colorado

**The end**