Gamma-ray binaries: microquasars and binary pulsar systems

SciNeGHE 2010
8th Workshop on Science with the New Generation of High Energy Gamma-ray Experiments
Trieste, September 8th - 10th 2010
The VHE gamma-ray Sky Map

38 extragalactic
60 galactic

LS I+61 303
LS 5039
PSR B1259-63

At HE
(E > 100 MeV)

LSI+61303, LS 5039 and Cygnus X-3: Fermi and AGILE

Cygnus X-1 and PSR B1259-63: AGILE
<table>
<thead>
<tr>
<th>Parameters</th>
<th>PSR B1259-63</th>
<th>LS I +61 303</th>
<th>LS 5039 Cygnus X-1</th>
<th>Cygnus X-3</th>
</tr>
</thead>
<tbody>
<tr>
<td>System Type</td>
<td>B2Ve+NS</td>
<td>B0Ve+NS?</td>
<td>O6.5V+BH?</td>
<td>O9.7I+ BH</td>
</tr>
<tr>
<td>Distance (kpc)</td>
<td>1.5 ± 0.2</td>
<td>2.0 ± 0.2</td>
<td>≈ 7</td>
<td>WR+ BH?</td>
</tr>
<tr>
<td>Orbital Period (d)</td>
<td>1237</td>
<td>26.5</td>
<td>3.9</td>
<td>5.6 ± 0.2</td>
</tr>
<tr>
<td>Eccentricity</td>
<td>0.87</td>
<td>0.72</td>
<td>~0</td>
<td></td>
</tr>
<tr>
<td>Inclination (º)</td>
<td>36</td>
<td>30 ± 20</td>
<td>20 ± 5</td>
<td></td>
</tr>
<tr>
<td>Periastron-apastron (AU)</td>
<td>0.7 - 10</td>
<td>0.1 - 0.7</td>
<td>0.1 - 0.2</td>
<td>0.2</td>
</tr>
<tr>
<td>Radio Structure (AU)</td>
<td>Jet-like ~140</td>
<td>Jet-like ~10-700</td>
<td>Jet 10^10^3</td>
<td>Jet 40 + ring</td>
</tr>
<tr>
<td>L_{radio}(0.1 - 100GHz)</td>
<td>(0.02 - 0.3) x 10^{31} (3 - 9) x 10^{33} (5 - 50) x 10^{33} 1 x 10^{37} ≈ 10^{38}</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>L_{X}(1 - 10keV) (erg s^-1)</td>
<td>(0.3 - 6) x 10^{33} (3 - 9) x 10^{33} (5 - 50) x 10^{33} 1 x 10^{37}</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Γ_{VHE}</td>
<td>27 ± 2</td>
<td>26 ± 2</td>
<td>20.6 ± 0.05</td>
<td>3.2 ± 0.6</td>
</tr>
</tbody>
</table>

Large luminosity and strong stellar wind

**might be a BH if i<25°**

(Casares et al. 2005)

Radio emitters and jet (like) radio structure
GeV/TeV emitting XRBs: Accretion vs non-accretion

Cygnus X-3
Cygnus X-1
PSR B1259-63
LS 5039 ?
LS I +61 303 ?
MQs as high-energy $\gamma$-ray sources

**Theoretical point of view**

<table>
<thead>
<tr>
<th>Leptonic models:</th>
<th>Hadronic models:</th>
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<tbody>
<tr>
<td><strong>SSC</strong></td>
<td><strong>Pion decay</strong></td>
</tr>
<tr>
<td><strong>EC</strong></td>
<td></td>
</tr>
<tr>
<td><strong>SSC+EC</strong></td>
<td></td>
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<tr>
<td>Bosch-Ramon et al. 2004 A&amp;A 417, 1075</td>
<td></td>
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<tr>
<td><strong>Synchrotron jet emission</strong></td>
<td>Markoff et al. 2003, A&amp;A 397, 645</td>
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</tbody>
</table>
Cygnus X-1

- HMXB, O9.71+BH
- 5 pc (8’) diameter ring-structure of bremsstrahlung emitting ionized gas at the shock between (dark) jet and ISM.

Steady flux below ~1% Crab Nebula flux

Strong evidence (4.1σ post trial significance) of intense short-lived flaring [1h-24h] episode discovered by MAGIC on 24-09-2006

- Soft spectrum (\(\Gamma = -3.2\)) between ~100 GeV and 1 TeV, with no break
- Extension below MAGIC angular resolution (~ 0.1°)
- Radio-nebula produced by the jet interaction with the ISM excluded
Detected up to 1 TeV. Orbital phase 0.9-1.0, when the BH is behind the star and photon-photon absorption should be huge: $\tau \sim 10$ at 1 TeV (Bednarek & Giovannelli 2007). Away from the BH might be the solution: flare in the jet? (Perucho & Bosch-Ramon 2008)

TeV excess right before the onset of a hard X-ray peak seen by Swift

Observations one day later reveal that no TeV excess was found during the maximum and decay phase of another hard X-ray peak

More simultaneous multi wavelength data is necessary to build models
TeV flare seen by MAGIC interpreted as a jet-cloud interaction. Protons in the jet interact with ions in a cloud of a clumpy wind from the companion, producing inelastic p-p collisions and pion decay which produces a flare in TeV gamma rays (Romero et al. 2010, A&A 518, 12)
Detected $>100$ MeV by AGILE (Sabatini et al. 2010, ApJ 712, 10 and ATel #2715) but not by Fermi/LAT (Abdo et al. 2010, ATels and Fermi/LAT blog). The detection spans 1 d in about 2 years of observations, and has a 5.3σ pre-trial significance, which is 4σ post-trial. It occurred during a low luminosity low/hard state.
Cygnus X-3  Strong radio outbursts

- HMXB, WR+NS?
  Orbital modulation of X-ray emission lines
  $i > 60$ NS, $i < 60$ BH

Development of arcsecond radio jets in CYGNUS X-3

Strong radio flares occur only when the source is in the soft state

If the non-thermal electrons responsible for either

the hard X-ray tails or

the radio emission during major flares

were accelerated to high enough energies then detectable emission in the γ-ray range, e.g., the GeV or TeV band, would be possible.

Given that major radio flares indicates the presence of hard X-ray tails, GeV and TeV emission should be searched for during those radio flares.
Fermi

Abdo et al. 2009, Science 326, 1512
Jet IC emission

$>100\text{ MeV}\gamma$-ray modulation in Cyg X-3

Anisotropic IC by jet relativistic $e^-$ with stellar photons along the orbit produces a modulation in the gamma-ray lightcurve (Khangulyan et al. 2008, MNRAS 383, 467)

Jet launched around a BH
- moderate bulk relativistic speed
- oriented not too far from the light of sight

Dubus et al. 2010, MNRAS 404, L55

- The $e^-$ emit synchrotron radio beyond the $\gamma$-ray emission zone on much larger scales

- A shock occurs in the wind because (Perucho et al. 2010, A&A)
  - wind mass-loss rate is very large
  - orbit very tight

Most $\mu$qs jets will interact much further away when their pressure matches that of the ISM. Any HE particles will find a much weaker radiation environment and will be less likely to produce a (modulated) IC $\gamma$-ray

Anisotropic IC $e^\pm$ pair cascade model. The optical depths for $\gamma$-rays created inside the binary system are huge. Escape of $\gamma$-rays with energies above a few tens of GeV is not very likely.

Young pulsar wind interacting with the companion star

PSR B1259-63 / LS 2883: O8.5-9 Ve (Negueruela et al. 2010) (dense equatorial circumstellar disk) + 47.7 ms radio pulsar, \( P = 3.4 \) yr, \( e = 0.87 \).

No radio pulses are observed when the NS is behind the circumstellar disk (free-free absorption).

The observed X-ray/soft gamma-ray emission was

- consistent with the shock-powered high-energy emission produced by the pulsar/outflow interaction

VHE gamma-rays are detected when the NS is close to periastron or crosses the disk (Aharonian et al. 2005, A&A 442, 1)

- significant variability
- power-law spectrum (\( \Gamma = 2.7 \)) explained by IC scattering processes
- the TeV, and radio/X-ray light curves, can be explained if the interaction with the circumstellar disk is considered (Chernyakova et al. 2006, MNRAS 367, 1201)
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Need of simultaneous TeV-X ray observations

The firm detection of VHE photons emitted at a true anomaly $\theta \approx -0.35$ of the pulsar orbit, i.e. already $\sim 50$ days prior to the periastron passage, disfavors the stellar disk target scenario as a primary emission mechanism, based on current knowledge about the companion star’s disk inclination, extension, and density profile.

AGILE detected transient gamma-ray emission from the PSR B1259-63 region \(\text{(Tavani et al. 2010, Atel \#2772)}\)

Not detected by \textit{Fermi} \(\text{(Abdo et al. 2010, Atel \#2780)}\)
Australian Long Baseline Array (LBA)
2.3 GHz

Total extension of the nebula: ~ 60 mas, or $140 \pm 24$ AU

The red crosses marks the region where the pulsar should be contained in each run

Periastron passage soon!!

Moldón et al. 2010 (submitted)
LS I +61 303  
**Dubious case**

- HMXB, B0Ve+NS?

COS-B γ-ray source CG/2CG 135+01  
Hermsen et al. 1977, Nature 269, 494

Radio (P=26.496 d)  

Optical and IR  
Paredes et al. 1994 A&A 288, 519

X-rays  

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Albert et al. 2006, Sci 312, 1771  


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Fermi}

MAGIC blue, 0.5-0.7  
VERITAS black, 0.5-0.8
Jet-like features have been reported several times, but show a puzzling behavior (Massi et al. 2001, 2004). VLBI observations show a rotating jet-like structure (Dhawan et al. 2006, VI Microquasars Workshop, Como, Setember 2006).

3.6cm images, ~3d apart, beam 1.5x1.1mas or 3x2.2 AU. Semi-major axis: 0.5 AU
**Pulsar scenario:** Interaction of the relativistic wind from a young pulsar with the wind from its stellar companion. A comet-shaped tail of radio emitting particles is formed rotating with the orbital period. We see this nebula projected (Dubus 2006, A&A 456, 801). UV photons from the companion star suffer IC scattering by the same population of non-thermal particles, leading to emission in the GeV-TeV energy range.

Not resolved yet the issue of the momentum flux of the pulsar wind being significantly higher than that of the Be wind, which presents a problem for interpretation of the observed radio structures (as pointed out by Romero et al 2007, A&A 474, 15).
LS 5039

- HMXB, O6.5V+NS?

**EGRET**

**3EG J1824-1514**

**HESS**


Aharonian et al. 2006, A&A 460, 743

(Khangulyan et al. 2008; Sierpowska-Bartosik & Torres 2008b)

- The emission is enhanced (reduced) when the highly relativistic electrons seen by the observer encounter the seed photons head-on (rear-on), i.e., at superior (inferior) conjunction
- VHE absorption due to pair production will be maximum (minimum) at superior (inferior) conjunction

The γ-ray data require a location of the production region at the periphery of the binary system at \(~10^{12}\) cm (Khangulyan et al. 2008, MNRAS 383, 467; Bosch-Ramon et al. 2008, A&A 489, L21)
The orbital plane has two degrees of freedom:

- Inclination of the orbit
- Longitude of the ascending node
# Summary

<table>
<thead>
<tr>
<th>Instrument</th>
<th>PSR B1259-63</th>
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<tr>
<td><strong>EGRET</strong></td>
<td></td>
<td>3EG J0241+6103</td>
<td>3EG J1824-1514</td>
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<tr>
<td>&gt;100 MeV</td>
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<tr>
<td><strong>AGILE</strong></td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
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<tr>
<td>30 MeV-50 GeV</td>
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<td><strong>FERMI</strong></td>
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<td></td>
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<td>30 MeV-300 GeV</td>
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<tr>
<td><strong>HESS</strong></td>
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<td>not visible</td>
<td>yes</td>
<td></td>
<td></td>
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<tr>
<td>&gt;100 GeV</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td><strong>MAGIC</strong></td>
<td>not visible</td>
<td>yes</td>
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<td>yes</td>
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<tr>
<td>&gt;60 GeV</td>
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<tr>
<td><strong>VERITAS</strong></td>
<td>not visible</td>
<td>yes</td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>

All of them are HMXBs

- All of them are radio emitters + jet (jet-like) structure
- All of them have a bright companion (O or B star) → source of seed photons for the IC emission and target nuclei for hadronic interactions

- NS and BH are among these detected XRBs
- VLBI monitoring of the jets along the orbit is crucial to understand some of these systems
- Multi-wavelength (multi-particle) campaigns are of primary importance

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