Gamma-ray Loud
X-ray Binaries

Yasunobu Uchiyama (SLAC)
*not* on behalf of the Fermi LAT Collaboration
Gamma-ray Loud Binaries: Two Categories

Compact Pulsar Wind Nebula

- PSR B1259-63

Microquasar

- LS 5039
- LS I +61°303
- HESS J0632+057
- 1FGL 1018.6-5856

Cerutti+11

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<table>
<thead>
<tr>
<th>Source</th>
<th>Type of Binary</th>
<th>$T_{\text{orb}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>PSR B1259-63</td>
<td>pulsar’s spin-down</td>
<td>3.4 years</td>
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<tr>
<td></td>
<td></td>
<td>TeV (HESS) &amp; GeV (Fermi-LAT)</td>
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<tr>
<td>LS 5039</td>
<td>unknown source of power</td>
<td>3.9 days</td>
</tr>
<tr>
<td></td>
<td></td>
<td>TeV (HESS) &amp; GeV (Fermi-LAT)</td>
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<td>LS I +61° 303</td>
<td>unknown source of power</td>
<td>26 days</td>
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<tr>
<td></td>
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<td>TeV (MAGIC/VERITAS) &amp; GeV (Fermi-LAT)</td>
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<tr>
<td>HESS J0632+057</td>
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<td>320 days</td>
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<td>TeV (HESS/MAGIC/VERITAS)</td>
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<tr>
<td>1FGL J1018.6-5856</td>
<td>unknown source of power</td>
<td>16.6 days</td>
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<tr>
<td></td>
<td></td>
<td>GeV (Fermi-LAT)</td>
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<tr>
<td>Cyg X-3</td>
<td>accretion onto BH/NS</td>
<td>4.8 hours</td>
</tr>
<tr>
<td></td>
<td></td>
<td>GeV (Fermi-LAT/AGILE) : transient</td>
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Fast Cooling of Electrons (& Positrons)

GeV-TeV electrons cool rapidly in the vicinity of a massive star.

Inverse-Compton scattering on stellar photons: (easily Klein-Nishina regime)
- $L^* \sim 10^{38}$ erg/s
- $d \sim 10$ AU
- $t_{\text{cool}} \sim 10$ sec (10 GeV)

Synchrotron cooling becomes dominant $E > \text{TeV}$.
- $B \sim 1$ G
- $t_{\text{cool}} \sim 10$ sec (10 TeV)

Fast acceleration is necessary
$$t_{\text{acc, min}} = \frac{r_g}{c} = 1 \left(\frac{E}{10 \text{ TeV}}\right)\left(\frac{B}{\text{gauss}}\right)^{-1} \text{ sec}$$

c) Mitya Khangulyan
Period 3.4 year \((e \sim 0.87)\)
- \(R_{\mathrm{orb}} \sim 0.7\) AU (at periastron)
- LS2883 Be (O star)
  - Circumstellar Disc
- Pulsar
  - spin period: 48 ms
  - pulsation disappears near periastron
  - \(L_{\mathrm{spin-down}} = 8 \times 10^{35}\) erg/s

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PSR B1259-63 provides unique opportunity to learn about pulsar wind on AU-scale

Hydrodynamical structure: relativistic wind vs non-relativistic wind

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Bogovalov+08
PSR B1259-63: X-ray Evolution

- Power-law
  - $\Gamma = 1.2 - 2.0$
  - $\Delta$ (electron index) = 1.6
- Absorption
  - modest column density
  - increase at disk entrance
- No pulsation found

Compiled by Chernyakova+09

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Compactified PWN Scenario

### Parameters

<table>
<thead>
<tr>
<th>Time</th>
<th>$\epsilon$</th>
<th>$\sigma$</th>
<th>$\gamma_1$</th>
<th>$p$</th>
<th>$E_m$ (TeV)</th>
<th>$\xi$</th>
<th>$\xi$</th>
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<tbody>
<tr>
<td>-15 days</td>
<td>0.1</td>
<td>0.01</td>
<td>$4 \times 10^5$</td>
<td>1.9</td>
<td>10</td>
<td>0.05</td>
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<td>+30 days</td>
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<td>$4 \times 10^5$</td>
<td>1.9</td>
<td>10</td>
<td>0.15</td>
<td>10</td>
</tr>
<tr>
<td>+618 days</td>
<td>0.1</td>
<td>0.01</td>
<td>$4 \times 10^5$</td>
<td>1.9</td>
<td>10</td>
<td>0.50</td>
<td>2</td>
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</tbody>
</table>

**Notes:**

- $\epsilon$: A fraction of the spin down power channeled into the accelerated $e^\pm$ pairs.
- $\sigma$: Magnetization factor of the pulsar wind.
- $\gamma_1$: Lorentz factor of the pulsar wind.
- $p$: Acceleration index.
- $E_m = \gamma m_e c^2$: Maximum energy of accelerated pairs.
- $\xi = r_s/d$: Distance of the termination shock from the pulsar divided by the pulsar-Be star separation.
- $\xi$: Parameter to describe the adiabatic loss rate.

- $\epsilon = 0.1$
- $\sigma = 0.01$ (poorly constrained)
- $\gamma_1 = 4 \times 10^5$
- $p = 1.9$
- $E_m = 10$ TeV (or larger)

**Additional Information:**

- X-ray break position: (Astro-H will check it)
- Fermi?

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PSR B1259-63: Synchrotron+IC Model

Compactified PWN Scenario

ε = 0.1
accelerated pair
spin down power

σ = 0.01 (poorly constrained)
magnetization factor

Γ₁ = 4x10⁵
wind Lorentz factor

X-ray break position
(Astro-H will check it)

ρ = 1.9
acceleration index

Eₘ = 10 TeV (or larger)
maximum energy

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Orbital period ~ 3.4 yr


the 1st periastron for Fermi-LAT
the 2nd periastron for Suzaku

The next one: April (2014) Astro-H?
Fermi-LAT surprised us: GeV flare after periastron

Suzaku Observations (Uchiyama)
80 ks, 40 ks (ToO), 20 ks

Fermi LAT light curve

GeV Flare!

photon index

Abdo+11
PSR B1259-63: Suzaku Observations

During the Fermi Flare

Off-set pointing

On

Off

PSR B1259:

\[ N_H = (0.513-0.518) \times 10^{22} \text{ cm}^{-2} \]

\[ \Gamma = 1.53-1.56 \]
PSR B1259-63: Suzaku Observations

Pre-Flare

**PSR B1259:**

\[ N_H = (0.573-0.575) \times 10^{22} \text{ cm}^{-2} \]

\[ \Gamma = 1.76-1.78 \]

During Flare

**PSR B1259:**

\[ N_H = (0.491-0.499) \times 10^{22} \text{ cm}^{-2} \]

\[ \Gamma = 1.42-1.50 \]

A “hard” straight power law up to 60 keV (for the first time)
PSR B1259-63: Suzaku & Fermi-LAT

Direct connection between Suzaku-Fermi

Suzaku:
very precise photon index $\Delta \Gamma \sim 0.02$

Graph showing flux vs. photon energy with data points for Suzaku (2011), Pre-Flare, During Flare, and HESS (2004) with a note indicating a significant connection.
PSR B1259-63: Suzaku & Fermi-LAT

Pre-Flare
During Flare

Suzaku: very precise photon index $\Delta \Gamma \sim 0.02$

Direct connection between Suzaku-Fermi
PSR B1259-63: Suzaku & Fermi-LAT

**Energetics:**

Spin-down power ≈ Gamma-ray luminosity
≈ e⁺e⁻ pair luminosity
(no room for ions)

Doppler boost with $\Gamma \approx 2$?
PSR B1259-63: Suzaku & Fermi-LAT

Direct connection between Suzaku-Fermi

Synchrotron up to GeV
(The 2\textsuperscript{nd} case after the Crab Nebula)

Synchrotron cooling: $t_{\text{syn}}$
Shock-acceleration timescale: $t_{\text{acc}} > t_{\text{acc, min}} = \frac{r_{g}}{c}$

$t_{\text{syn}} = t_{\text{acc, min}} \rightarrow$

The cutoff energy of synchrotron spectrum
$\varepsilon_{c} = \frac{(9/4)mc^{2}}{\alpha_{f}} = 160 \text{ MeV (electron)}$
$= 300 \text{ GeV (proton)}$
- Period 3.9 days ($e \sim 0.3$)
- $R_{\text{orb}} \sim 0.1$ AU
- O6.5V($\sim 20$ $M_{\text{sun}}$)
- Compact object
  - Unknown (1.5-5 $M_{\text{sun}}$)
- Relativistic outflow
  - extending to $\sim 10$ AU
- No evidence for accretion disk

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LS 5039: Suzaku continuous 1.5 orbit

- **Suzaku-XIS (0.5-10 keV)**
- **Suzaku-PIN (15-70 keV)**
- **H.E.S.S.**

**Photon Index**
- Takahashi+09
- \( \Gamma = 1.45 - 1.60 \)

**Absorption**
- Constant
- Modest column density
- No pulsation found
LS 5039: Long-term Stability


Figure 2. (a) Orbital light curves in the energy range of 1–10 keV. Top: Suzaku XIS data with a time bin of 2 ks. Overlaid in the range of $\phi = 0.0–2.0$ is the same light curve but shifted by one orbital period (open circles). Bottom: comparison with the past observations. Each color corresponds to XMM-Newton (blue, cyan with each bin of 1 ks, and green with each bin of 2 ks), ASCA (red with each bin of 5 ks), and Chandra (magenta with each bin of 2 ks). Fluxes correspond to unabsorbed values. The blue solid lines show periastron and apastron phase and the red dashed lines show superior conjunction and inferior conjunction of the compact object.

(b) Close up in $1.2 \leq \phi < 1.8$. 

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LS 5039: Synchrotron(X)-IC(TeV) Model

- Adiabatic Cooling Time
- TeV gamma-rays
- VHE photon index
- X-ray
- 1 – 100 GeV gamma-rays

Takahashi+09
Kishishita 09
Abdo+09

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$t_{\text{cool}} \sim 1 \text{ sec (adiabatic loss)}$

Acceleration timescale: $t_{\text{acc, min}} = \frac{r_g}{c}$

$= 1 \left( \frac{E}{10 \text{ TeV}} \right) \left( \frac{B}{G} \right)^{-1} \text{ sec}$

Extreme electron acceleration, namely

"acceleration time ~ $t_{\text{acc, min}}$"

must be realized.
Summary

Extreme Electron Accelerators In Our Galaxy

Acceleration timescale: \( t_{\text{acc}} \sim \frac{r_g}{c} \)

PSR B1259-63

LS 5039

The Crab Nebula