Interacting pulsar winds in high-mass binaries

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Emission powered by spindown of a pulsar

Ram pressure equilibrium between pulsar wind and stellar wind gives rise to small-scale pulsar wind nebula with a bow shock structure, set by

$$\eta = \frac{\dot{E}/c}{\dot{M} v_w}$$

Termination shock is close to pulsar, about $10^4 R_{\text{LC}}$
**High-mass gamma-ray binaries**

Sources of non-thermal emission up to GeV and TeV gamma-rays

<table>
<thead>
<tr>
<th>system</th>
<th>star</th>
<th>radio pulsar</th>
<th>$P_{\text{orb}}$ (days)</th>
<th>HE or VHE gamma-rays ?</th>
</tr>
</thead>
<tbody>
<tr>
<td>PSR B1259-63</td>
<td>Be</td>
<td>yes</td>
<td>1237</td>
<td>yes</td>
</tr>
<tr>
<td>LS 5039</td>
<td>O</td>
<td>?</td>
<td>3.9</td>
<td>yes</td>
</tr>
<tr>
<td>LS I +61 303</td>
<td>Be</td>
<td>(?)</td>
<td>26.5</td>
<td>yes</td>
</tr>
<tr>
<td>HESS J0632+057</td>
<td>Be</td>
<td>?</td>
<td>320</td>
<td>yes</td>
</tr>
<tr>
<td>1FGL J1018.6-5856</td>
<td>O</td>
<td>?</td>
<td>16.6</td>
<td>yes</td>
</tr>
</tbody>
</table>

(*) there are also **low-mass** gamma-ray binaries (tomorrow)
Well-established phenomenology in LS 5039

orbital modulation

Good constrains on 3.9 day orbit
Possible gamma-ray emission sites

- bow-shocked pulsar wind
- back-shocked pulsar wind
- shocked stellar wind
- pulsar wind
- pulsar magnetosphere
Use relativistic hydro simulation as input provides consistent description in shocked pulsar wind emission model of:

- shock extension
- doppler boosting
- adiabatic cooling
Conditions in the shocked pulsar wind

\[ B \sim 1/d_p \text{ at shock (assumed perpendicular)} \]

Field is passive so induction equation \( \Rightarrow B \sim \Gamma n r \)

see Lamberts et al. 2013 and Dubus et al. 2015 for code & setup
Particle evolution in a post-processing step

1- inject particles at shock
four global parameters:
- power-law slope
- acceleration timescale ($E_{\text{max}}$)
- pulsar power ($E_{\text{min}}$)
- magnetisation ($B$)

2- evolve along streamlines with radiative & adiabatic cooling.

G. Dubus, dec 2015
3D calculation for particle emission

- Synchrotron and inverse Compton emission
  eccentric orbit, relativistic effects, anisotropic scattering & pair production on stellar photons
- phase-dependent spectra & orbital modulation

in units of orbital separation
Doppler boosting shapes the modulation

[inclination]

face-on

i=0°
i=25°
i=50°
i=90°

VHE

>100 GeV

1–10 keV

X-ray
Influence of particle injection parameters

- magnetic field
  - $\sigma$
- $E_{\text{min}}$
- $E_{\text{max}}$
- slope

- $\zeta_b = 10$
- $\zeta_p = 10$
- $\xi = 100$
- $s = 1.5$
- $s = 2.5$

Tough to reproduce hard VHE spectrum + level of X-ray emission in LS 5039
LS 5039 requires two particle populations

Power-law with hard slope $E^{-1.5}$ + Maxwellian with $\Gamma \approx 5000$
Orbital variability in reasonable agreement

modulation set by Doppler boost $\Rightarrow i \approx 35^\circ$

(for assumed $\eta = 0.1$)
First RHD-based model of LS 5039’s emission

- emission concentrated at head of bow shock
- modulation mostly due to Doppler boosting
- power-law is radiatively-efficient, adiabatic cooling negligible
- maxwellian carries most of the energy but radiatively-inefficient

- particle acceleration extremely fast (Bohm)
- hard power-law, pulsar wind magnetisation $<\sigma> \approx 1$
- shock-driven reconnection in gamma-ray binaries?

requires (Sironi & Spitkovsky 2011)

$$\kappa \frac{R_{lc}}{R_{ts}} \geq 1$$

easier in binaries!