On the physics of colliding stellar-pulsar winds

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Outline

1. Introduction: previous work and context
2. Dynamics of the stellar/pulsar wind interaction structure
3. Radiation sites and related mechanisms/processes
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• PSR B1259–63 (Johnston et al. 1992) is the only binary system confirmed as hosting a massive star and a powerful non-accreting pulsar.

• The whole Galaxy may contain several tens of these objects (e.g. Portegies et al. 1999).

• The star and the pulsar produce winds that interact where their ram pressures balance each other.

• The interaction between the star and the pulsar winds lead to the formation of two shocks at both sides of the contact surface.
Studies of the source radiation

- Maraschi & Treves proposed in 1981 that LS I +61 303, yet of unclear nature, produced gamma-rays through the interaction of the winds from the star and a pulsar.

- Tavani & Arons explored in the mid-90s the processes of non-thermal radiation from PSR B1259−63 (detected at GeV and TeV by Fermi and HESS).

- Several groups (Martocchia et al.; Dubus et al.; Torres et al.; Neronov, Chernyakova and Zdziarski; Romero et al.; Khangulyan, Aharonian, Bosch-Ramon, Bogovalov, Zabalza, Paredes, Ribó & Moldón; Bednarek et al.; McSwain et al.) have observationally and theoretically studied the possibility that other powerful binary systems hosted also young non-accreting pulsars, in particular LS 5039, LS I +61 303, or HESS J0632+057; other sources: 1FGL J1018.6−5856?

- Synchrotron+inverse Compton (HE) from the stellar-facing shock and synchrotron emission further out (LE), but Evil...
Studies of the source dynamics

- Several effects have been *discovered* through tough numerical work. Several groups have studied different aspects of the pulsar / stellar wind interaction:
  - inner interaction region, important effects (relativistic, 2D, magnetic field): Bogovalov et al. 2008, 2012
  - middle scale global structure of the interaction region (2D, motion): Lamberts et al. 2012 (non-relativistic) and Bosch-Ramon et al. 2012 (relativistic)
  - larger global structure, radiation (no dynamic sim.): Bosch-Ramon & Barkov 2011, Bednarek & Sitarek 2013

- Results emphasize that the pulsar wind re-accelerates after the shock, cooling adiabatically (minor role for $B$ and anisotropies), and is shaped afterwards by orbital motion.
Flow acceleration, stellar disc disruption, large scale interactions...

(Bogovalov et al. 2008; Romero et al. 2007)

(B-R & Barkov 2011; Okazaki et al. 2011)
Magnetic field, spiral fate, dense disc interactions...

(Bogovalov et al.; Lamberts et al.; Takata et al.; 2012)
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Mass, momentum and energy

- The main parameter characterizing the two-winds interaction structure at binary scales is

\[ \eta = \frac{L_{sd}}{\dot{M}_* V_* c} \approx \frac{L_{36.5}}{\dot{M}_{-8} V_{2000}} \]

This determines the dominant source of momentum flux. For normal massive-star winds (\( \dot{M}_* > 10^{-8} M_\odot/\text{yr} \)), and not very powerful pulsars (\( L_{sd} < 3 \times 10^{36} \dot{M}_{-8} \text{ erg/s} \)):

\[ \eta < 1 \rightarrow \text{the interaction structure bends over the pulsar} \]

- The pulsar wind is more energetic than the stellar one by

\[ 2c\eta/V_* \sim 30\eta_{0.1} \]

but the stellar-wind mass rate dominates by a factor

\[ \Gamma_p c/\nu \eta \sim 10^9 \Gamma_6 \eta_{0.1}^{-1} \]
Orbital re-orientation of the flows

- As in massive-star binaries, orbital motion leads to a spiral pattern of the interaction structure of step length $l = v_r T$.
- With mass coming from the star but energy from the pulsar,

$$ v_r \sim 10^9 L^{1/2} \dot{M}^{-1/2} \text{cm/s} $$

so $l \sim 10^{15} v_9 T_6$, much smaller than $l = 3 \times 10^{16} c T_6$, the ballistic value for the pulsar wind.
- However, flow bending (and $4\pi$-pulsar wind termination) starts at the distance where Coriolis forces become dominant over the pulsar wind momentum rate (e.g. Eichler & Usov 1993, Melatos 1995; B-R & Barkov 2011)

$$ x_0 \approx 7 \times 10^{12} L^{1/2} \dot{M}_w^{-1/2} \text{cm} $$
Differences with a non-relativistic case

- Despite the shape similarity at small scales, pulsar and stellar winds interact differently from two stellar winds:
  - Energetics is concentrated in the pulsar zone
  - A diluted, hot and fast flow is confined by heavy slow matter
  - The relativistic inertia is $\sim \Gamma^2$ times larger than the non-relativistic one
  - Large contrast in densities and velocities
  - Instabilities and shocks develop differently
- Even for moderate mixing, the pulsar wind suffers strong changes in density and velocity, and shocks.
- Even without instabilities and mixing, much of the kinetic energy is likely to go to heat.
Instabilities on binary scales

(Lamberts et al. 2012b)

(B-R et al. 2012)
Spiral flow evolution (Left: $h'_{\text{th}}/h_T \uparrow$, $\gamma\beta \downarrow$; Right: $\rho c^2 \uparrow$, $P \downarrow$)
Linear flow evolution (Left: $h'_\text{th} / h_T$; Right: $\rho c^2$)
Linear flow evolution (Left: $\gamma\beta$; Right: $P$)
Dynamical features at middle scales

(B-R, Barkov, Khangulyan & Perucho 2012)
Dynamical features at middle scales

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Summarizing...
**Acceleration and emitting regions**

- **Star-facing shock:** Efficient or inefficient acceleration: relativistic shock + fast advection?
  - escape/adiabatic cooling — IC + synchrotron — *deep* emitter — high/very high energies

- **Flow re-acceleration:** Some acceleration — adiabatic cooling — boosting (narrow cone)
  - IC + synchrotron — *deep/extended* emitter — very high energies

- **Velocity shear:** Efficient acceleration via shear?
  - mass-load and wind-slow down
  - *deep/extended* emitter — IC + synchrotron + pp/Bremss. — very high energies

- **Termination shock:** Efficient particle acceleration: relativistic shock plus strong turbulence?
  - IC + synchrotron — no so-*deep/extended* emitter — very high energies

- **Turbulent back-flow:** Stochastic acceleration?
  - IC + synchrotron — extended emitter — low energies

- **Free pulsar wind:** Pulsar wind physics!
  - bulk motion vs hotter wind (converter mechanism)? — IC vs IC + synchrotron — *deep/extended* emitter — high energies

- **Far regions:** Stellar+pulsar wind merging — IC + synchrotron + ? — ISM interaction
A clock, non-linear dynamics, optical thickness: complex but workable

- The pulsar wind itself and the inner acceleration regions can efficiently produce HE radiation and re-process it.
- The whole spectrum can be affected by contributions from regions of different time and spatial scales, with an important re-processed component.
- Even for effective energy dissipation at small scales, strong adiabatic cooling implies that much of the energy is transported away in an inhomogeneous flow.
- The stellar wind and the orbital motion confine the pulsar wind to dissipative trajectories with the ISM at the far end.
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Final remarks

- A characterization of the simplest stellar-pulsar colliding wind scenario is arising.
- Several acceleration regions can be identified, which can be linked to the emitting zones through (thorough) hydro-radiation studies.
- Radiation reprocessing can be properly computed when a model of the emitter structure is available.
- The next step should rely on a source by source basis plus a better characterization (at least) of the stellar wind.
- **Stellar and pulsar wind physics, and non-thermal physics in general (particle acceleration, shocks and turbulence, etc.) can profit from detailed studies even when just a handful of sources are available.**