Pulsed emission and flaring activity of the Crab pulsar unified through magnetic reconnection in its striped wind?

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A (very) brief reminder

Motivations
- Pulsed (very) high energy emission
- Flares in the Crab

Magnetic reconnection in the wind
- The striped wind model
- Single current sheet dynamics and VHE pulsed emission
- Double current sheet dynamics and flaring activity

Conclusions
A (very) brief reminder

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4 Conclusions
From observations

- period $P \in [1 \text{ ms}, 1 \text{ s}]$
- period derivative $\dot{P} \in [10^{-18}, 10^{-15}]$
- spin-down losses well constrained

\[ L_{sp} = 4 \pi^2 I \dot{P} P^{-3} \approx 10^{24-31} \text{ W} \]

very different from black holes or accreting neutron stars

- inferred magnetic field estimate by dipole radiation

\[ B = 3.2 \times 10^{15} \sqrt{P \dot{P}} = 10^{5-8} \text{ T} \]
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- detection of pulsed emission from the Crab at 200-400 GeV
- compatible with the spectrum in the Fermi band
- spectrum as a broken power low rather exponential cut-off

(Aleksic et al, 2012)
Crab Flares: light-curves

- unexpected fluctuations in the gamma-ray flux increase by a factor 10
- variations on a day scale
  - strong flares (F) lasting one day
  - weak waves (W) lasting one or two weeks
- short but powerful flares ($E \approx 10^{34} \text{ J}$)
- isotropic power = sizeable fraction of the spin-down luminosity

Figure: *The Crab nebula.*

Figure: *Temporal evolution of the Crab flares seen in gamma-rays (Striani et al., 2013).*
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The striped wind

Near the star: a rotating magnetic dipole

At large distances: a relativistic striped wind

- $\vec{\Omega}$: rotation axis
- $\chi$: magnetic axis inclination with respect to $\vec{\Omega}$
- $\zeta$: line of sight inclination with respect to $\vec{\Omega}$

Presence of a current sheet wobbling around the equatorial plane.

- hot and magnetized plasma in the sheet
- relativistic beaming $\Gamma_{\text{vent}} \gg 1$

$\Rightarrow$ pulsed emission
Reconnection in the striped wind: two regimes

Current sheets are usually prone to magnetic reconnection through

- plasma resistivity in MHD description.
- kinetic effects in a Vlasov description (electron inertia, anisotropic pressure tensor).

When radiation is included, we distinguish two regimes for which efficiency is limited

1. by radiation reaction: cut-off Lorentz factor of particles $\gamma$ determined by $\tau_{\text{sync}} = \tau_{\text{acc}}$
   $\Rightarrow$ exponential particle distribution cut off

   $$n(\gamma) \propto \gamma^{-p} e^{-\gamma/\gamma_{\text{rad}}} \quad \Rightarrow \quad \varepsilon F_{\varepsilon} \propto e^{-\varepsilon^{1/3}}$$

2. by escape: cut-off Lorentz factor of particles $\gamma$ determined by the escape probability from the acceleration region $R_{\text{Larmor}} = \delta_{\text{thickness}}$
   $\Rightarrow$ sharper cut off

   $$n(\gamma) \propto \gamma^{-p} e^{-\gamma^2/\gamma_{\text{sI}}} \quad \Rightarrow \quad \varepsilon F_{\varepsilon} \propto e^{-\varepsilon^{1/2}}$$

(Mochol & Pétri, 2015)
Figure: Crab synchrotron and SSC spectrum for different parameters of the model. CTA sensitivity is shown in grey.
Figure: Vela synchrotron spectrum for different parameters of the model. SSC is not shown because too weak.
Different high energy particle tails distributions
⇒ different sub-exponential cut-off spectra
Parameters: $\Gamma, \varepsilon_d, r_d, p$

<table>
<thead>
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<th></th>
<th>$\Gamma$</th>
<th>$\varepsilon_d$</th>
<th>$r_d$</th>
<th>$p$</th>
<th>$\kappa$</th>
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</thead>
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<td>Crab</td>
<td>23</td>
<td>0.01</td>
<td>36</td>
<td>2-2.4</td>
<td>$10^4$</td>
</tr>
<tr>
<td>Vela</td>
<td>18</td>
<td>0.01</td>
<td>12</td>
<td>1.2</td>
<td>14</td>
</tr>
</tbody>
</table>

The transition line between both reconnection regimes depends only on the observables $P, \dot{P}$ as

$$\frac{\dot{E}_{38}^{3/2}}{P_{-2}} \sim 0.002$$

Figure: *The two reconnection regimes in the $P - \dot{P}$ plot.*
Simple estimates about the flares

Comparing the time scales
- too long for the Crab pulsar (33 ms)
- too short for the nebula evolution (years)
- size of emitting region, \( L_f \approx c \Delta t \approx 1 \text{ld} \approx 3.10^{13} \text{ m} \approx 0.01 \ R_{TS} \).

Possible locations
- within the striped wind \( r_L < R_f < R_{TS} \).
- at the termination shock \( R_f = R_{TS} \).
- within the nebula \( R_f > R_{TS} \).
Flares in the unshocked wind!

- timescale of reconnection $\tau \approx \sqrt{\tau_A \tau_D} = S^{1/2}$
  as in classical MHD
  $\tau_A$ Alfven timescale
  $\tau_D$ diffusion timescale
  $S$ Lundquist number
- outflow not relativistic
- reconnection rate to slow for the flares
  $\Rightarrow$ tearing instability unable to explain fast rising time
- the answer: double tearing mode
  (Baty et al., 2013; Pétri et al., 2015)

Figure: Relativistic pair plasma reconnection (Hesse & Zenitani, 2007).
Numerical setup

Double Harris current sheet

\[ B_x = B_0 \left( 1 + \tanh\left( \frac{y - y_0}{L} \right) - \tanh\left( \frac{y + y_0}{L} \right) \right) \]

- width of one current sheet, \( L = 1 \)
- separation 2 \( y_0 = 6 \, L \)
- uniform temperature \( T = 1 \)
- normalization: magnetic field \( B^2 = 2 \) and density \( \rho = 1 \)
- specific heat ratio \( \Gamma = 4/3 \)
- Alfven speed

\[ v_A = c \sqrt{\frac{\sigma}{\sigma + 1}} \]

Two free parameters

- magnetization \( \sigma \gg 1 \)
- Lundquist number \( S = L \, c/\eta \gg 1 \)

Figure: The two current sheets in the simulations.
Simulation example

Figure:

Double tearing mode with $\sigma = 12$, $S = 3200$. 
Simulation example: four stages

1. linear evolution of the DTM as an antisymmetric pattern
2. saturation: Rutherford regime (maximal size of the islands with diffusion)
3. secondary instability: fast non-linear evolution
4. relaxation to the final state: magnetic field dissipated into bulk motion and particle thermalization

Figure: Maximum flow velocity $V_x$ with $\sigma = 12$.

Figure: The four phases in the DTM (Baty et al., 2013).
Flares in the Crab

Time scales
- observational constrain $\Delta T \lesssim \tau_r \approx 10 \text{ hr} \Rightarrow \Gamma \lesssim 150$
- consistent with $\Gamma \approx 20 - 50$ from Pétri & Kirk (2005)

Energetics
- energy release in a flare $10^{34} \text{ J}$
- local magnetic field in the flare around 2 T
- wave nature of the striped wind implies emission at $r \approx 50 r_L$.
- luminosity according to $L = D^4 L'$
- in agreement with the 2011 flare $L_{\text{>100 MeV}} \propto \varepsilon_c^{3.42 \pm 0.86}$ (Buehler et al., 2012)

Figure: Spectra of several Crab flares.
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Relativistic magnetic reconnection in pulsar striped wind can explain

1. pulsed gamma-ray emission in MeV-Gev (TeV)
   - particle acceleration in two regimes: radiative cooling or size-limited
   - for Crab spectrum, a new pulsed SSC component at (sub)TeV? (CTA)
   - wind Lorentz factor $\Gamma_{\text{Crab}} < 100$ and $\Gamma_{\text{Vela}} < 50$

2. DTM good candidate to explain short and powerful gamma-ray flares in strongly magnetized plasmas
   - striped wind is a natural place where to expect double/multiple tearing modes
   - wind parameters consistent with independent estimates (pulsed gamma radiation/optical polarization)
PhD position in theoretical high-energy astrophysics

Contribution of multipolar fields to radio and high-energy emission of pulsars

Schematic view of a pulsar.

Example of radio-polarisation.

Website: http://amwdb.u-strasbg.fr/HighEnergy/spip.php?article271
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