Gamma-ray emission as a probe of relativistic reconnection in pulsar winds

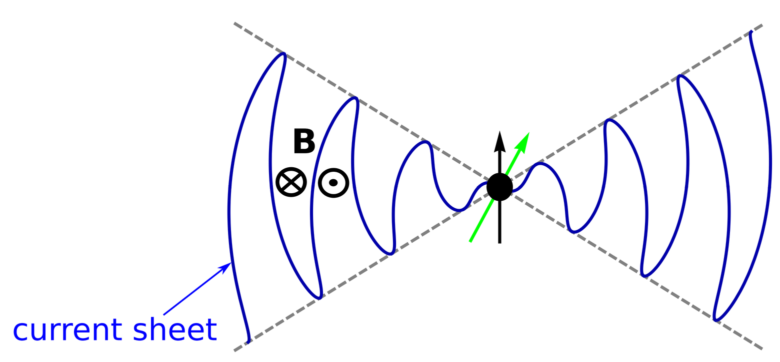
Iwona Mochol[1,2] and Jérôme Pétri[1]

[1] Observatoire Astronomique de Strasbourg, France
[2] Nuclear Physics Institute, Polish Academy of Sciences, Kraków, Poland

Relativistic reconnection is thought to be an efficient mechanism of energy dissipation in magnetically dominated outflows. It has been considered in the context of blazar flares, Crab flares, and also as a process underlying pulsar emission.
Here we investigate the latter scenario and we show that the physics of particle acceleration at the reconnection sites in pulsar winds is imprinted on the gamma-ray spectra of Fermi pulsars. In the very most energetic ones, like Crab, the acceleration is limited by radiative cooling, while in less powerful pulsars, like Vela, the particle energization is limited by the size of the reconnecting current sheet. In each case the synchrotron spectrum emitted by the accelerated particles has a subexponential tail.
Our model predicts a new spectral component due to synchrotron self-compton process, extending up to tens of TeV in the Crab spectrum. It is expected to be above the sensitivity of the upcoming experiment CTA.

1. Pulsar winds and pulsed emission

- pulsar winds highly magnetized $\sigma \gg 1$ and relativistic $\Gamma \gg 1$
- they consist of a pair plasma and electromagnetic fields, forming the "striped wind": cold stripes of opposite magnetic polarity separated by a current sheet [1]
- current sheet is prone to reconnection – a process of energization of particles, which emit synchrotron radiation, observed as pulsed [2, 3]



current sheet is corrugated when the rotator is oblique

$B_\phi \propto r^{-1}$

2. The model

- outside the light cylinder $r_L = cP/2\pi$ (where P is the pulsar period) reconnection sets in
- within the distance r_{diss} a fraction ε_d of initial magnetic energy is dissipated to the plasma
- in the wind comoving frame particles are energized to a power-law distribution $n'(\gamma') \propto \gamma'^{-s} \times$ cutoff by reconnection electric fields: $E' \sim \tau B'$
- reconnection rate τ is a phenomenological parameter; we find it by comparying the wind comoving frame the reconnection timescale $t'_{rec} \sim \varepsilon_d \Gamma r_L/(\tau c)$ with the wind expansion time $t'_{exp} \sim r_{diss}/(\Gamma c)$:

$$\tau = \varepsilon_d \Gamma^2/\hat{r}, \quad \hat{r} = r_{diss}/r_L$$

- pressure (energy density) of the energized plasma constitutes a fraction of the magnetic energy density; this constrains the particle number density:

$$\varepsilon_d \frac{B'^2}{8\pi} = p = \frac{mc^2}{3}\int n'(\gamma')\gamma' d\gamma'$$

- synchrotron emission of the energized particles is calculated by integrating synchrotron emissivity over 3D volume [4, 5]
- **from the fit of the spectrum to the data we determine Γ, $\hat{r}$, ε_d and s; having them, we calculate SSC component**

3. Acceleration at reconnection sites

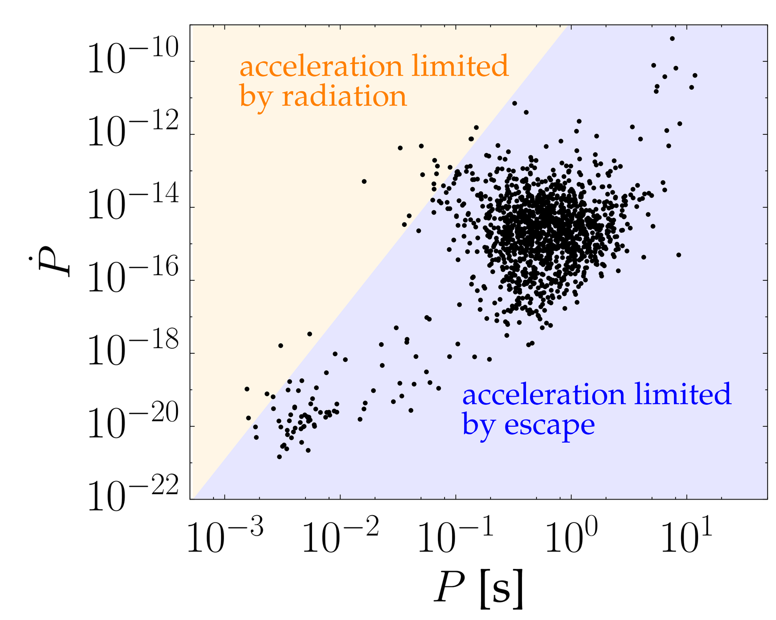
We suggest that particle acceleration can proceed in two regimes:

1. limited by radiation reaction – the cut-off Lorentz factor of particles γ'_{rad} is determined by the synchrotron cooling timescale equal to the acceleration timescale in the reconnection electric field $E' \approx \tau B'$; in this case the particle distribution cuts off exponentially.

$$n'(\gamma') \propto \gamma'^{-s} e^{-\gamma'/\gamma'_{rad}} \quad (1)$$

2. limited by escape – when the particle cut-off Lorentz factor γ'_{sl} is determined by the escape from the acceleration region (gyroradius comparable with the size of the current sheet $\Delta \times 2\pi r_L$); in this case the cut-off can be sharper [6]

$$n(\gamma') \propto \gamma'^{-s} e^{-\gamma'^2/\gamma'^2_{sl}} \quad (2)$$



$\gamma'_{rad} < \gamma'_{sl}$ when

$$\frac{\dot{E}_{38}^{3/2}}{P_{-2}} > 0.005\left(\frac{\hat{r}}{10}\right)\left(\frac{0.1}{\zeta}\right)\left(\frac{0.1}{\Delta}\right)\left(\frac{\Gamma}{100}\right)^{3/2}\left(\frac{\varepsilon_d}{0.01}\right)^{1/2}$$

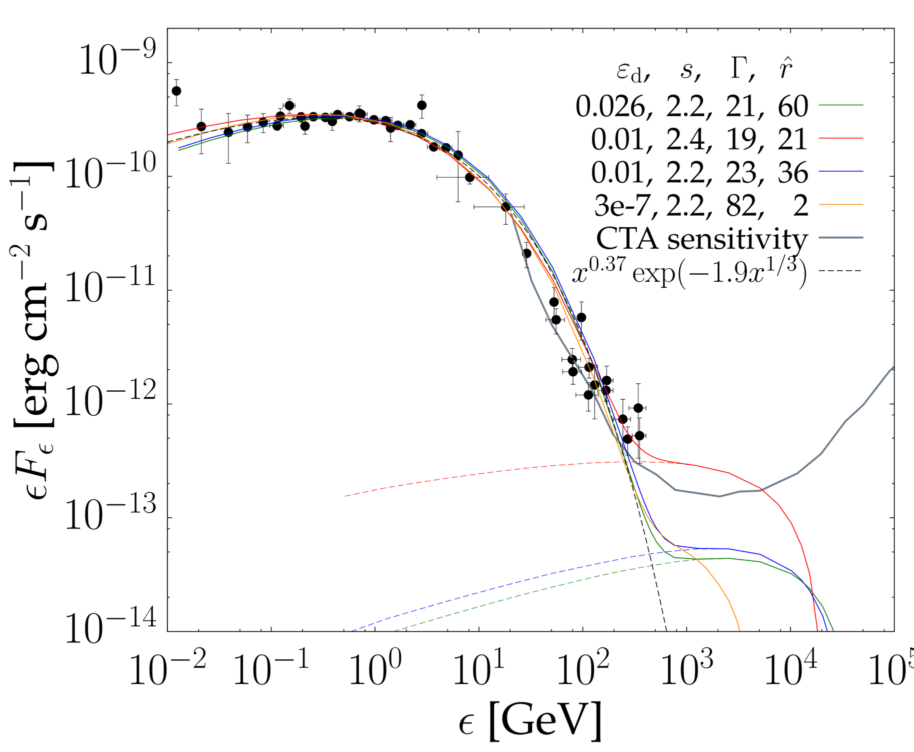
($\dot{E}$ – pulsar spin down power, $X_i = X \times 10^i$ in CGS)

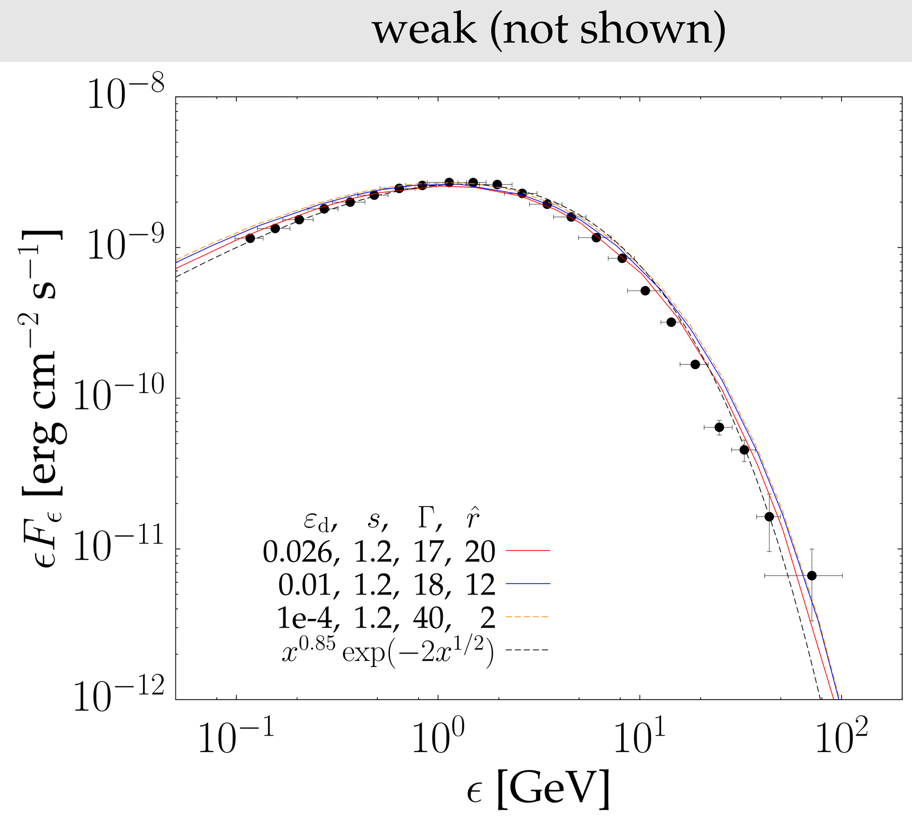
Each distribution implies a different asymptote of the synchrotron spectrum – strightforward to obtain from the flux integral by using the steepest descent method [5].

4. Crab vs Vela

acceleration limited by	radiation	escape
particle distribution	$n'(\gamma') = n_0 \gamma'^{-s} e^{-\gamma'/\gamma'_{rad}}$	$n'(\gamma') = n_0 \gamma'^{-s} e^{-\gamma'^2/\gamma'^2_{sl}}$
index	soft $s > 2$	hard $s < 2$
asymptote of synchr. spectrum	$x^{1.3-(s+0.6)/3} e^{-1.9x^{1/3}}$	$x^{1.3-(s+0.6)/4} e^{-2x^{1/2}}$
SSC component	$\epsilon_{max} \approx 2\Gamma\gamma'_{rad} mc^2 \approx 3.6\,\Gamma_1^{5/2} P_{-2}^{1/2} \varepsilon_{d,-2}^{1/2} \dot{E}_{38}^{-1/4}$ TeV	weak (not shown)

Crab data: [7]
Vela data: [8]





5. Conclusions

- We propose that pulsed gamma-ray emission gives insight into the physics of relativistic reconnection in pulsar winds:

  the **structure** of the current sheet is imprinted on pulsar **lightcurves**,
  the **physics** of particle acceleration – in gamma-ray **spectra**

- Particle acceleration can be limited either by radiative cooling or by the particle escape from the acceleration region (depending on pulsar observables $\dot{E}^{3/2}/P$)
- In the Crab spectrum, a new SSC component at tens of TeV (CTA) will constrain the model (wind) parameters
- We put an upper limit on the Lorentz factor of the Crab wind $\Gamma \lesssim 100$ and of the Vela wind $\Gamma \lesssim 50$; in good agreement with previous works on optical polarization signatures [3] and Crab flares [9]

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