Pair production and $\gamma$-ray emission in pulsars: A modern view

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Pulsar: rapidly rotating magnetized neutron star

“Electric lighthouse”
Pulsar: Cosmic Electrical Lighthouse

NB: Pulsars are non-thermal emitters
Plasma creation in the polar cap

Cascades are electromagnetically driven
Limit cycle: series of discharges

No particles extraction from the NS

\[ \text{particles} \rightarrow v \]

- electrons
- positrons
- $\gamma$-rays

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Free particle extraction from the NS

Particles' momenta: \( p \sim [0, 10] \)

- Electrons
- Positrons
- Photons

"cold" flow - no pairs

\( 0 < j/j_{GJ} < 1 \)

"hot" flow - pair production

\( j/j_{GJ} > 1 \)

\( \chi = 0^\circ \)
\( \chi = 30^\circ \)
\( \chi = 60^\circ \)
\( \chi = 90^\circ \)

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Full cascade

Synchrotron cascade

Curvature Radiation

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Cascade Efficiency

Fraction of particle energy going into synchrotron and curvature radiation

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Particle acceleration

\[ \log \epsilon_{\pm, \text{acc}} \]

\[ \rho_c \]

\[ \epsilon_{\pm, \text{acc}} \approx 5 \times 10^7 \chi_a^{2/7} \xi_j^{1/7} \rho_{c, 7}^{4/7} P^{-1/7} B_{12}^{-1/7} \]
Multiplicity of polar cap cascade: $\kappa \sim 10^5$

Dependence on $\rho_c$ partially cancels out:

- small $\rho_c \rightarrow$ high splitting efficiency, but low primary particle energy
- large $\rho_c \rightarrow$ low splitting efficiency, but high primary particle energy
Discharge: RS flow

- electrons
- positrons
- $\gamma$-rays

- Low heating of NS surface
- Duty cycle: can be as low as $h_{\text{gap}}/R_{\text{NS}} \sim 1/100$ (for Crab)
Discharge: super-GJ SCLF

- electrons
- positrons
- $\gamma$-rays

- Low heating of NS surface
- Duty cycle: $\sim 1/\text{few}$

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PSR J1057-5226: Polar cap emission?

J1057-5226, P=0.1971s
H=14999
d = 0.30 pm 0.00, D = 0.31 pm 0.00
PKS 1.4 GHz
> 0.1 GeV

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Pairs and $\gamma$-rays in Pulsars
Electric field in resistive magnetosphere
uniform high $\sigma$

(Kalapotharakos et al. 2014)
Curvature radiation in magnetosphere with non-uniform $\sigma$

$$v = \left( \frac{E \times B}{B^2 + E_0^2} + \frac{f B}{B} \right) c$$

$$\frac{d \gamma_L}{dt} = f \frac{q_e c E_\parallel}{m_e c^2} - \frac{2 q_e^2 \gamma_L^4}{3 R_{CR}^2 m_e c}$$

(Kalapotharakos et al. 2014)
γ-ray Emitting Regions

(Kalapotharakos et al. 2014)
Peak Separation ($\Delta$) vs Radio Lag ($\delta$)

(Kalapotharakos et al. 2014)
Conclusions

• Particles can be accelerated faster and at lower altitudes
• $\gamma$-ray emission from polar caps is at lower energies ($\sim 10 - 100$ MeV)
• Maximum multiplicity of polar cap cascades $\kappa \sim 10^5$
  • Maximum multiplicity is not sensitive to pulsar parameters
  • Plasma distribution is non-uniform
  • Inclinations angle should be very important factor determining the overall pulsar pair multiplicity

• The bulk of $\gamma$-ray emission seems to come from the current sheet region outside the light cylinder