A Synchrotron-Self Compton Model for Pulsar Emission

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VERITAS and MAGIC detection of the Crab pulsar

Pulsed emission up to at least 400 GeV and possibly 1 TeV!

Aliu et al. 2011
Ansoldi et al. 2015

- Cutoff of combined spectrum is not simple exponential
- Extension of Fermi spectrum or separate component (inverse Compton)?
- Is the Crab unique or do other pulsars have > 100 GeV emission as well?
VHE emission from other pulsars?

Vela detected by HESS (Stegmann 2014, talk by B. Rudak)

Geminga not detected by VERITAS (Aliu et al. 2015)
Synchrotron self-Compton emission

**Essential ingredients:**
1) Energetic particles
2) High synchrotron emission level

**Pair cascade spectrum (polar cap)**

**High-energy pulsar spectra**

Energetic pair spectrum and high non-thermal X-rays produce high level of SSC

SSC emission from middle-aged pulsars will be much lower
Pair cascades produce an abundance of charged particles to supply charges to magnetosphere.

Cascades are likely time-varying.

Pair cascades above the PC are necessary for coherent radio emission.

Pair cascades produce an abundance of charged particles to supply charges to magnetosphere.

\[ M_\pm \approx 10^3 - 10^5 \]

Timokhin 2010, Timokhin & Arons 2013

Timokhin & Harding 2015
Kalapotharakos et al. 2012
Color: charge density, Streamlines: magnetic field

- 3D Cartesian grid with resolution 0.02 $R_{LC}$ from $r = 0.2 - 2 R_{LC}$
- Match with dipole down to “real” pulsar surface
- Inject primary $e^-$ and pairs at points on surface between $r_{ovc} = 0.95 - 0.99$ ($e^-$) and $0.91 - 0.95$ (pairs)

Particle trajectories in force-free magnetic field, $R_*$ to $2R_{LC}$

$$\beta = \frac{E \times B}{B^2 + E_0^2} + \int \frac{B}{B} = 1$$
Simulation of pulsar radiation

Primaries and pairs emit curvature (CR), synchrotron (SR) and SSC

Primaries and pairs emit curvature (CR), synchrotron (SR) and SSC by resonant absorption of radio photons when

\[ \varepsilon_B = \gamma \varepsilon_R (1 - \beta \cos \theta) \]

(Lyubarski & Petrova 1998)

\[ \gamma_{res} = 3 \times 10^3 \frac{B_6}{\varepsilon_{R, GHz} (1 - \beta \cos \theta)} \]
Synchrotron self-Compton emission

\[
\frac{d\dot{N}_{\text{SSC}}(\epsilon_s)}{d\epsilon_s d\Omega_s} = \int dE \ n_{\pm}(E) \int d\Omega \int d\epsilon \ n_{\gamma}(\epsilon, \Omega) \frac{d\sigma_{\text{KN}}(\epsilon, \Omega)}{d\epsilon d\Omega} (1 - \beta \cos \theta)
\]

Pair cascade spectrum (polar cap)

Synchrotron photon density

\[
n_{\gamma}(\epsilon, \Omega) = \frac{1}{c} \int dr \ r^2 \frac{\epsilon_{\text{SR}}(\epsilon, \Omega, r)}{r_s^2}
\]

SSC calculation in two steps:

1. SR emission, SR photon density
2. SSC emission
SSC emission from Crab pulsar

Harding & Kalapotharakos 2015 \( \alpha = 45^0, \, \zeta = 60^0, \, M_+ = 3 \times 10^5 \)

- **High**
  - \( B_{LC} = 1 \times 10^6 \, \text{G} \)
  - \( L_R = 2200 \, \text{mJy kpc}^2 \)

- **Small**
  - \( R_{LC} = 1.5 \times 10^8 \, \text{cm} \)

All good for SR and SSC
SSC from Crab-like pulsar B0540-69

Harding & Kalapotharakos 2015 \[ \alpha = 45^0, \zeta = 70^0, M_+ = 3 \times 10^5 \]

High
\[ B_{LC} = 3.6 \times 10^5 \text{ G} \]

Small
\[ R_{LC} = 1.5 \times 10^8 \text{ cm} \]

But
\[ L_R = 1000 \text{ mJy kpc}^2 \]

So, smaller SR and SSC

Fermi data – Ackermann et al. 2015, see poster by Martin
SSC emission from Vela pulsar

Harding & Kalapotharakos 2015

$\alpha = 75^0$, $\zeta = 60^0$

\[ M_+ = 6 \times 10^3 \]
\[ 10^5 \]

Low
$B_{LC} = 4 \times 10^4 \text{ G}$
$L_R = 392 \text{ mJy kpc}^2$

Larger
$R_{LC} = 4.3 \times 10^8 \text{ cm}$

So, much smaller
SR and SSC
SSC emission from MSPs

Harding & Kalapotharakos 2015 \( \alpha = 45^0, \zeta = 80^0 \)

High
- \( B_{\text{LC}} = 7.3 \times 10^5 \) G
- \( L_R = 1210 \) mJy kpc\(^2\)

Small
- \( R_{\text{LC}} = 1.4 \times 10^7 \) cm

\( \alpha = 75^0, \zeta = 70^0 \)

SR spectra peak \( \sim 1-10 \) MeV

SSC peak \( \sim 100 \) GeV but lowered by KN reductions

High
- \( B_{\text{LC}} = 1 \times 10^6 \) G
- \( L_R = 6000 \) mJy kpc\(^2\)

Small
- \( R_{\text{LC}} = 7.6 \times 10^6 \) cm
• Synchrotron radiation from pairs can produce non-thermal X-rays in Crab-like pulsars and MSPs
• Prediction of synchrotron peak ~1-10 MeV in MSPs is testable with Compton or pair telescopes
• SSC from pairs produce VHE emission in Crab and Crab-like pulsars (high $B_{LC}$ and $M_+$)
• VHE possibly detectable from MSPs but only for high pair multiplicity
• No detectable SSC from Vela-like pulsars
• Next step: use E-field distribution from global models (see talks by Kalapotharakos and Philippov, poster by Brambilla) and self-consistent pairs
Particle trajectories

Crab, $\gamma_\star = 6 \times 10^4$

- $(d\gamma/dt)^{SR}$
- $p_\perp$
- $(dp_\perp/dt)^{abs}$
- $\varepsilon_{SR}$
- $(d\gamma/dt)^{SSC}$

Resonant absorption
relativistic $p_\perp \rightarrow$ SR