IC model of pulsar high energy emission

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**Abstract.** We discuss growing evidence that pulsar high energy emission is generated via Inverse Compton mechanism. We reproduce the broadband spectrum of Crab pulsar, from UV to very high energy gamma-rays - nearly ten decades in energy, within the framework of the cyclotron-self-Compton model. Emission is produced by two counter-streaming beams within the outer gaps, at distances above $\sim 20$ NS radii. The outward moving beam produces UV-X-ray photons via Doppler-booster cyclotron emission, and GeV photons by Compton scattering the cyclotron photons produced by the inward going beam. The scattering occurs in the deep Klein-Nishina regime, whereby the IC component provides a direct measurement of particle distribution within the magnetosphere. The required plasma multiplicity is high, $\sim 10^6 - 10^7$, but is consistent with the average particle flux injected into the pulsar wind nebula.

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**EVIDENCE IN FAVOR OF IC SCATTERING AS THE MAIN SOURCE OF HIGH ENERGY PHOTONS**

The pulsar high energy emission is a complicated unsolved problem in high energy astrophysics which has been been under intensive study for nearly four decades. *Geometrical* models, based on the idea of the outer gap [1], are very successful in explaining the basic features of the observed $\gamma$-ray light curves, while there seems broad consensus that the particle accelerator is located in the outer magnetosphere, the radiation physics remain controversial.

Recently, motivated by the new discoveries of VHE emission from MAGIC and especially VERITAS collaborations [2, 3] we argued in favor of inverse Compton origin of pulsar high energy emission [4, 5, 6]. Let us here briefly summarize the arguments in favor of IC scattering:

**Maximal energy of curvature emission in Crab.** The curvature emission in pulsars is limited to energies below

$$\epsilon_{br} = (3\pi)^{7/4} \frac{\hbar}{(ce)^{3/4} \eta^{3/4} \sqrt{\xi B_{NS}^{3/4} R_{NS}^{9/4} P^{7/4}}}$$

where $R_L$ is the light cylinder radius, $P$ is pulsar period of rotation, $\xi$ is a dimensionless scaling parameter $\xi = R_c/R_L$, $R_c$ is the radius of curvature of magnetic field lines, $B = B_{NS}(R_{NS}/R)^3$, where $B_{NS}$ is the magnetic field on the surface of the neutrons star...
and $R_{NS}$ the star's surface and $\eta = E/B \leq 1$ is the relative strength of the accelerating electric field, [4].

If the $\gamma$-ray photons are due solely to the curvature emission of a radiation reaction-limited population of leptons, the spectrum above the break must show an exponential cut-off. The detection of the Crab pulsar by VERITAS collaboration [3] clearly demonstrated the non-exponential cut-off above the spectral break, see Fig. 1.

![High energy spectrum of Crab demonstrating the non-exponential spectral break](image)

**FIGURE 1.** Left: High energy spectrum of Crab demonstrating the non-exponential spectral break inconsistent with curvature emission [figure from 3]. Right: Fits to the high energy tail of the Geminga spectrum: power law (solid line, $\chi^2 = 0.1$) and exponential cut-off (dashed line, $\chi^2 = 2$).

**Maximal energy of curvature emission and observed breaks.** Lyutikov, Ref. [4], compared the observed spectral breaks of Fermi pulsars from the first Fermi catalogue with the predicted breaks due to curvature emission, Eq. (1), see Fig. 2. A significant number of pulsars the ratio is close to one and for one pulsar, PSR J1836 + 5925, the ratio is even larger than one. In order to explain the spectral break for these pulsars as a result of curvature radiation, an accelerating electric fields should be close to or even larger than the magnetic field at the light cylinder. What is more, the example of Crab demonstrates that the spectral break may not be related to the maximal curvature photons.

**Geminga: non-exponential break.** Reanalyzing the Fermi spectra of the Geminga pulsar above the break, Lyutikov, Ref. [5], found that it is well approximated by a
simple power law without the exponential cut-off, making Geminga’s spectrum similar to that of Crab, Fig. 1. Vela’s broadband $\gamma$-ray spectrum is equally well fit with both the exponential cut-off and the double power law shapes.

**Patterns of relative intensities in the Crab of the leading and trailing pulses repeated in the X-ray and $\gamma$-ray regions**, see Fig. 3.

![FIGURE 3.](image)

**FIGURE 3.** Evolution of the Crab profile with energy. Note that that the lower-energy evolution of the increasing interpulse to main pulse ratio is mirrored in the $\gamma$-rays. Such behavior is expected in synchrotron-self-Compton model.

The broadband spectrum of Crab pulsar, from UV to very high energy gamma-rays - nearly ten decades in energy - can be reproduced within the framework of the cyclotron-self-Compton model. Emission is produced by two counter-streaming beams within the outer gaps, at distances above $\sim 20$ NS radii. The outward moving beam produces UV-X-ray photons via Doppler-booster cyclotron emission, and GeV photons by Compton scattering the cyclotron photons produced by the inward going beam. The scattering occurs in the deep Klein-Nishina regime, whereby the IC component provides a direct measurement of particle distribution within the magnetosphere. The required plasma multiplicity is high, $\sim 10^6 - 10^7$, but is consistent with the average particle flux injected into the pulsar wind nebula [6], Fig. 4.

These arguments demonstrates that the inverse Compton scattering may be the dominant high energy emission mechanism in majority of pulsars.
FIGURE 4. Left: The broadband spectrum of the Crab approximated with the CSC model. The IC bump in the KN regime provides a direct measurement of the bulk particle distribution, while the high energy part of cyclotron bump constrains the very high energy tail of the particle distribution. This is a fit over nearly ten decades in energy, using only a handful of parameters. Right: The parallel distribution function $f(\delta)$

IMPLICATIONS

• For IC scattering occurring in the Klein-Nishina regime, the particle distribution in the gap does not evolve towards a stationary distribution and thus is intrinsically time-dependent.
• In a radiation reaction-limited regime of particle acceleration the gamma-ray luminosity $L_\gamma$ scales linearly with the pulsar spin-down power $\dot{E}$, $L_\gamma \propto \dot{E}$, and not proportional to $\sqrt{\dot{E}}$ as expected from potential-limited acceleration.
• The importance of Compton scattering in the Klein-Nishina regime also implies the importance of pair production in the outer gaps. We suggest that outer gaps are important sources of pairs in pulsar magnetospheres.
• Cyclotron motion of particles in the pulsar magnetosphere may be excited due to coherent emission of radio waves by streaming particles at the anomalous cyclotron resonance, Ref. [7]. Thus, a whole range of Crab non-thermal emission, from coherent radio waves to very high energy $\gamma$-rays - nearly eighteen decades in energy - may be a manifestation of inter-dependent radiation processes.

REFERENCES

1. K. S. Cheng, C. Ho, and M. Ruderman, ApJ 300, 500–539 (1986).
2. Aliu and MAGIC Collaboration, Science 322, 1221– (2008), 0809.2998.
3. VERITAS Collaboration, and E. e. Aliu, Science 334, 69– (2011), 1108.3797.
4. M. Lyutikov, N. Otte, and A. McCann, ApJ 754, 33 (2012), 1108.3824.
5. M. Lyutikov, ApJ 757, 88 (2012), 1203.1860.
6. M. Lyutikov, ArXiv e-prints (2012), 1208.5329.
7. M. Lyutikov, G. Machabeli, and R. Blandford, ApJ 512, 804–826 (1999), arXiv:astro-ph/ 9802197.