Multi-wavelength emission and particle acceleration in pulsar magnetospheres

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Emission : Objectives & Methods

Pulsed emission

- constrain the geometry of the pulsar and observer line of sight.
- identify the radio, X-ray and γ-ray emission mechanisms.

Methods

- use young radio-loud γ-ray pulsar light-curves.
- radio emission altitude and angle constrained by RVM [1] model.
- γ-ray emission from the striped wind.

Results

- consistent radio and γ-ray geometries.
- localisation of non-thermal X-ray emission height.

1. Rotating Vector Model

Possible sites for pulsed emission

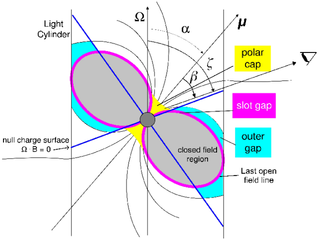

Fig. – *Emission models (Breed et al.).*

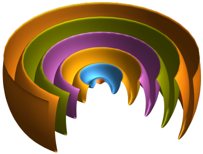

Fig. – *Pulsar striped wind current sheet.*

Basic picture

- magnetosphere filled with $e^{\pm}$ plasma corotating with the neutron star up to r_{L}.
- corotation charge $\rho_{\mathrm{GJ}} = -2\,\varepsilon_0\,\vec{\Omega}\cdot\vec{B}$.
- no acceleration in regions where $\rho = \rho_{\mathrm{GJ}}$ because $E_{\parallel} = 0$.
- but acceleration in regions where $\rho \neq \rho_{\mathrm{GJ}}$ because $E_{\parallel} \neq 0$.

Four important sites

- polar cap : star surface R.
- slot gap : from R to r_{L}.
- outer gap : from null-line to r_{L}.
- striped wind : outside r_{L}.

Location of gaps tells you where emission comes from.

Emission model

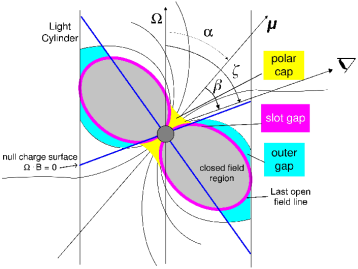

***Fig. –** Emission models.*

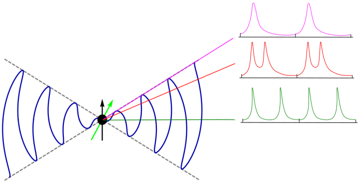

***Fig. –** Pulsar striped wind current.*

Essentially three parameters to fit

1. magnetic **dipole inclination** α.
2. observer **line of sight inclination** ζ $(= \alpha + \beta)$.
3. possible **shift in phase** ϕ_s between observation and model.

Computation of radio, X-ray and γ-ray pulse profile depending on α and ζ.

Radio atlas (polar cap) depending on $\{\alpha, \zeta\}$

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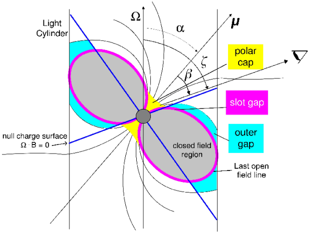
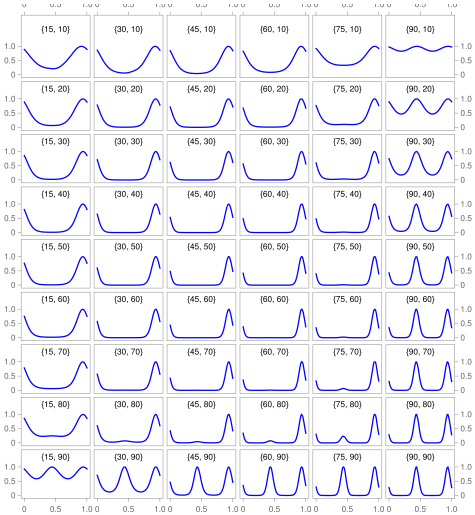


***Fig. –** Radio from polar cap region.*



Atlas of radio pulse profiles for $\alpha = \{15^\circ, 30^\circ, 45^\circ, 60^\circ, 75^\circ, 90^\circ\}$ from left to right column and $\zeta = \{0^\circ, ..., 90^\circ\}$ in steps of 10° in the format $\{\alpha, \zeta\}$.

X-ray atlas (slot gap) depending on $\{\alpha, \zeta\}$

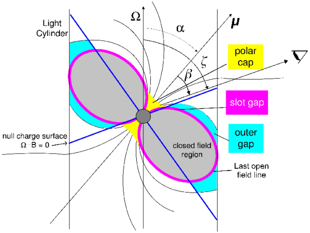
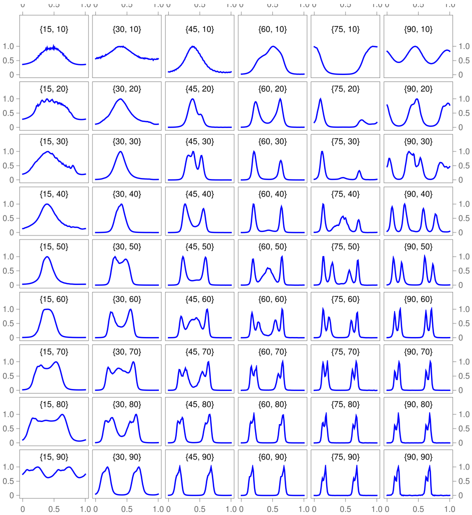


***Fig. –** X-ray from* ***slot cap region**.*



X-ray light curves for $\alpha = \{15^\circ, 30^\circ, 45^\circ, 60^\circ, 75^\circ, 90^\circ\}$ from left to right column and $\zeta = \{0^\circ, ..., 90^\circ\}$ in steps of 10° in the format $\{\alpha, \zeta\}$.

γ-ray atlas (striped wind) depending on $\{\alpha, \zeta\}$

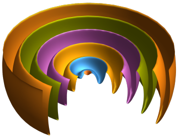
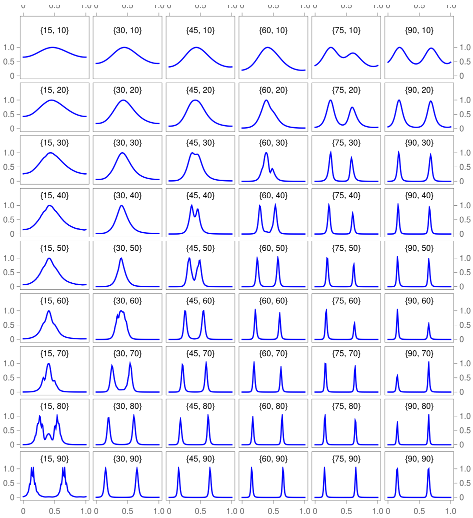


Fig. – *γ-ray from striped wind (outside the magnetosphere).*



Atlas of γ-ray light curves for $\alpha = \{15^\circ, 30^\circ, 45^\circ, 60^\circ, 75^\circ, 90^\circ\}$ from left to right column and $\zeta = \{0^\circ, ..., 90^\circ\}$ in steps of 10° in the format $\{\alpha, \zeta\}$.

Young pulsars : radio polarization and γ-rays

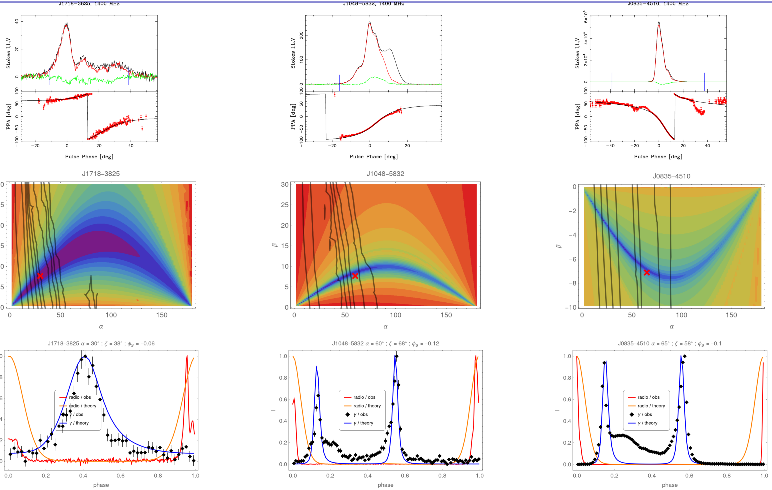


Fig. – *Best fit from polarization and gamma-rays.*

(Pétri & Mitra, 2021)

Young pulsar : fit from γ-rays only

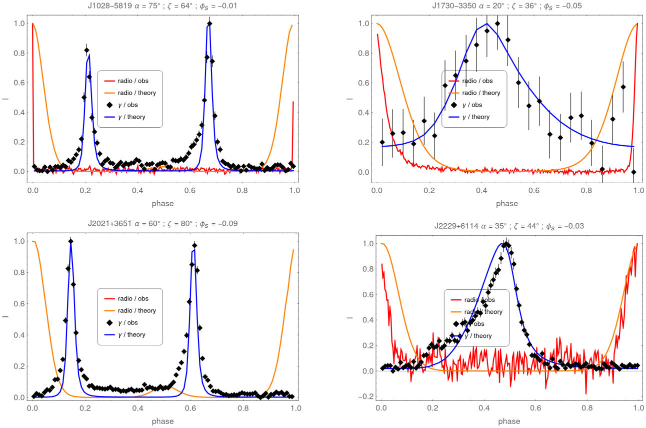


Fig.* – *Best fit parameters and γ-ray light-curves of the young radio loud γ-ray pulsar without RVM fits.

(Pétri & Mitra, 2021), for MSP see **(Benli et al., 2021)**

PSR J2229+6114 : non thermal X-ray fitting

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Strategy

- find the angles (α, ζ) from joint radio and γ-ray.
- a good fit given by $(\alpha, \zeta) = (45°, 38°)$.
- adjust the X-ray emission site to fit the X-ray pulse profile.

Observations and results

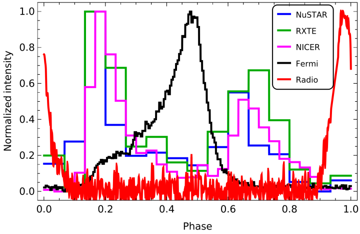

***Fig.** – Multi-λ pulse profiles.*

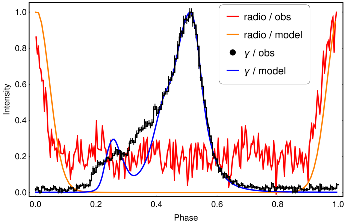

***Fig.** – Joint radio and γ-ray fit.*

PSR J2229+6114 : non-thermal X-ray fitting.

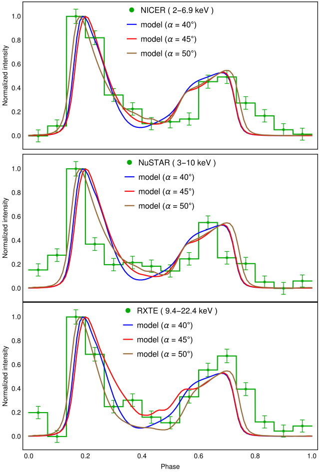

***Fig.** – Fitted light-curves in X-ray.*

Deduced parameters for good fits

	α	ζ	χ^2_ν
NICER	45	46	1.41
(1–10 keV)	50	32	1.17
RXTE	45	48	1.73
(9.4–22.4 keV)	50	34	1.83
NuSTAR	45	48	3.03
(3–10 keV)	50	48	1.65

Emission geometry

- **emission height** $r/r_{\rm L} \in [0.2, 0.55]$.
- line of sight inclination agrees with γ-ray fit $\zeta \in [34°, 48°]$.

(Pétri et al., 2024)

Particle acceleration : Objectives & Methods

Physical challenges

- compute particle acceleration and radiation in a realistic environment.
- impact of radiation reaction on particle acceleration efficiency.
- follow accurately particle trajectories.

Methods

- design a particle pusher for ultra-strong fields based on analytical solutions of the equation of motion.
- long term task : a fully electromagnetic Particle-In-Cell (PIC) code for ultra-strong fields and ultra-relativistic particles.

Landau-Lifshitz equation

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with 4-velocity u^i, electromagnetic tensor F^{ik}, particle charge and mass q, m, proper time τ

$$\frac{du^i}{d\tau} = \frac{q}{m} F^{ik} u_k + \frac{q\,\tau_m}{m} \partial_\ell F^{ik} u_k u^\ell + \frac{q^2\,\tau_m}{m^2} \left[F^{ik} F_{k\ell} u^\ell + (F^{\ell m} u_m)(F_{\ell k} u^k) \frac{u^i}{c^2} \right] \quad (1)$$

with the radiation damping time scale (for electrons)

$$\tau_m = \frac{q^2}{6\,\pi\,\varepsilon_0\,m\,c^3} = \frac{2}{3}\frac{r_e}{c} \approx 6.26 \times 10^{-24}\ \text{s.} \quad (2)$$

Two important parameters of the problem

1. strength parameter

$$a = \omega_{\rm B}/\Omega \gg 1$$

2. radiation damping parameter

$$b = \Omega\,\tau_m \ll 1$$

Particle tracking around neutron stars

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Inject charged particles and let them evolve.

- electron.
- proton.
- iron.

In the electromagnetic field of a neutron star

- millisecond pulsar : $B \sim 10^5\ T$ and $a \sim 10^{13}$.
- normal pulsar : $B \sim 10^8\ T$ and $a \sim 10^{18}$.
- magnetar : $B \sim 10^{11}\ T$ and $a \sim 10^{21}$.

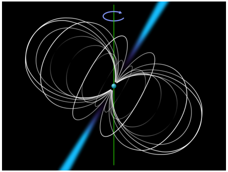
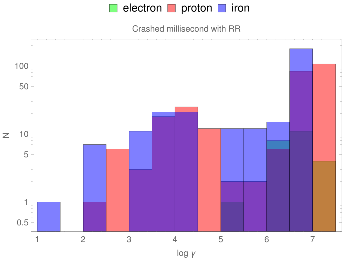


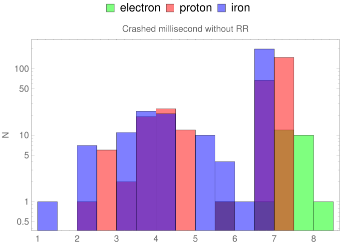
Fig.* – *Rotating dipole field.

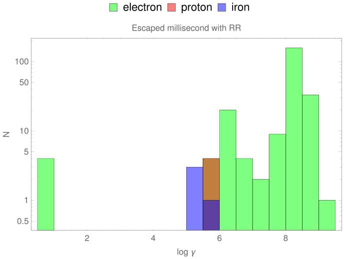
Three kind of motion

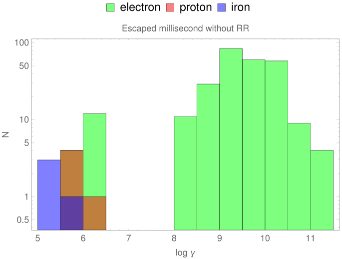
- trapped.
- crashed.
- escaped.

Particles escaping and crashing

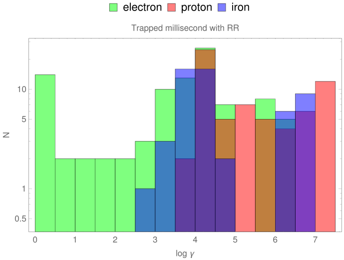


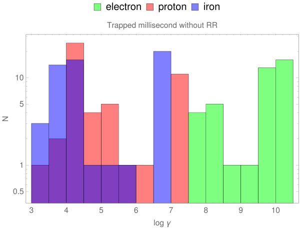


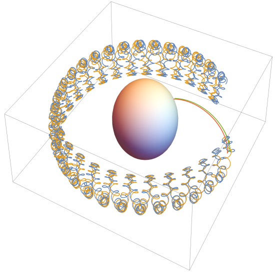




Particles trapped around neutron stars







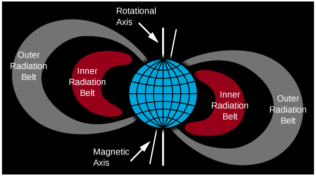


***Fig.* – 2D view of Earth Van Allen radiation belt.**

Conclusions & Perspectives

Time-aligned radio/X-ray/γ-ray pulse profiles

- very efficient to constrain the geometry of the magnetic dipole.
- radio polarization reduces even more the uncertainties.
- non-thermal X-ray emission site between radio and γ-ray.
- determination of non-thermal X-ray emission altitude and extension.

Particle acceleration

- neutron stars are very efficient particle accelerators.
- in rotating neutron stars, particles with Lorentz factors up to 10^{12}.

Perspectives

- search for other good candidates seen in radio/X-ray/γ-ray.
- compute multi-wavelength spectra up to TeV.
- redo the analysis with 3PC.
- implement the pusher into a PIC code.