Linear Acceleration Emission in Radio Pulsars

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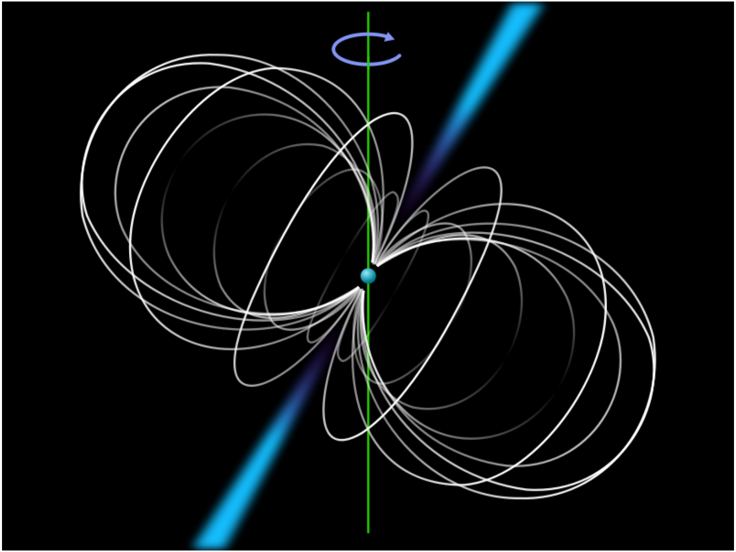
Outline

- Pulsars:
  basic introduction
- Pulsar magnetosphere:
  vacuum model, corotating model, oscillating model
- Pulsar Emission:
  radio (coherent), high energy (incoherent)
- Linear Acceleration Emission

Common cartoon



(Wikipedia)

Magnetosphere models

- Vacuum model:
  - magnetic dipole radiation in vacuum
- Corotating model:
  - magnetosphere populated by corotating plasma
- Unacceptable features present in both models
- Standard models borrow features from both models

Vacuum electric field

- Interior of a neutron star is an excellent conductor, $\sigma = \infty$
- Ohm's Law, $\mathbf{J} = \sigma \left[\mathbf{E} + (\Omega_* \times \mathbf{x}) \times \mathbf{B}\right]$, in corotating frame inside the star implies $\mathbf{E} = 0$
- In an inertial rest frame inside the star $\mathbf{E} = -(\Omega_* \times \mathbf{x}) \times \mathbf{B}$
- Boundary conditions imply a nonzero charge density at the surface of the star
- $E_z \neq 0$ along $\mathbf{B}$ above star

Vacuum Model

- Vacuum field can accelerate charges to cause pair cascade
  - no longer vacuum

- Magnetic dipole radiation in vacuum at frequency Ω_*
  - transverse wave cannot propagate below plasma frequency

- EM torque due to escaping radiation causes alignment of magnetic and rotation axes
  - not observed

Corotating Model

- A corotating electric field, $\mathbf{E} = -(\Omega_* \times \mathbf{x}) \times \mathbf{B}$, must be present everywhere
- Corotation speed exceed speed of light beyond light cylinder
- Separate magnetosphere into closed and open regions (Sturrock 1971)
- A minimum charge density, $\rho_{\mathrm{GJ}} = \varepsilon_0 \nabla \cdot \mathbf{E}$, required to maintain corotation (Goldreich & Julian 1969)

Pair Formation Fronts

- $\rho_{\mathrm{GJ}} = \varepsilon_0 \left(-2\boldsymbol{\Omega}_* \cdot \mathbf{B} + \boldsymbol{\Omega}_* \times \mathbf{x} \cdot \nabla \times \mathbf{B}\right)$
- ρ_{GJ} can be set up by E_z, resulting in charge-limited outflow
- Additional source of charge required to maintain ρ_{GJ}
- Deviations from ρ_{GJ} leads to a (vacuum) 'gap'
  - vacuum-type E_z develops
- Particles accelerated resulting in pair cascade
- Concentrated in narrow range of heights: PFFs.

Oscillating model

- Parallel electric field screened above PFF

- Common assumption: time-independent magnetosphere (Arons & Scharlemann 1979)

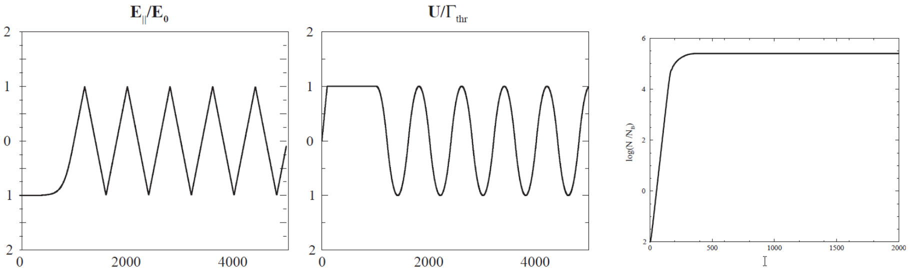
$$\nabla \times \mathbf{B} = \mu_0 \mathbf{J} + \underbrace{\frac{1}{c^2} \frac{\partial \mathbf{E}}{\partial t}}_{\text{ignored}}$$

- Any mismatch between $\mu_0 \mathbf{J}$ and $\nabla \times \mathbf{B}$ must be balanced by a displacement current

- This leads to an oscillating model (Sturrock 1971)

Large-amplitude oscillations

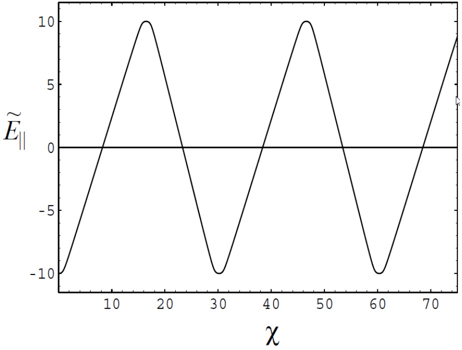
- Numerical solution of one dimensional equations (fluid, continuity, Maxwell's)



(Levinson et al. 2005)

Large-amplitude Electrostatic Wave

- Outward propagating superluminal large-amplitude electrostatic waves (LAEW)



(Luo and Melrose 2008)

Pulsar Emission

- Radio emission: $T_{\mathrm{b}} > 10^{25}$ K $\implies$ coherent
- Coherent mechanisms
  - curvature emission by bunches (localization in $\mathbf{p}$ & $\mathbf{x}$)
  - reactive instability (localization in $\mathbf{p}$)
  - maser (negative absorption)
- LAE is a maser mechanism (Melrose 1978)
- High energy emission: synchrotron, IC and RIC (Melrose 2004)

Procedure

- Integrate
$$\frac{\mathrm{d}p^{\mu}(\tau)}{\mathrm{d}\tau} = qF^{\mu\nu}(\tau)\,u_{\nu}(\tau)$$
to obtain $u^{\mu}(\tau)$ and $x^{\mu}(\tau)$

- Fourier transform the current density
$$J^{\mu}(k) = q\int_{-\infty}^{\infty}\mathrm{d}\tau\; u^{\mu}(\tau)\,e^{ikx(\tau)}$$

- Power radiated per unit frequency per unit solid angle
$$\eta(k) = \frac{1}{T}\frac{\omega^2}{16\pi^3\varepsilon_0 c^3}\left|e^{*}_{\mu}(k)\,J^{\mu}(k)\right|^2$$

LAE in LAEW

- Characteristic maximum frequency of the LAE is $\omega_c \approx \Omega \gamma_{\max}^2 \sim \omega_p \gamma_{\max}^{3/2}$
- For $\Omega \sim 10^6\ s^{-1}$ and $\gamma_{\max} \sim 10^6 - 10^7$ we have $\omega_c \sim 10^{18-20}\ s^{-1}$
- LAE may explain pulsar emission up to hard X-rays, but not γ-rays.
- Power spectrum $\propto \omega^{4/3}$ at $\omega \ll \omega_c$

(Melrose, Rafat & Luo 2009; Melrose & Luo 2009)

LAE in other fields

- Particle
  - in a constant electric field;
  - in a waveform describing a double layer; and
  - undergoing simple harmonic motion

- Characteristic cutoff frequency $\omega_\mathrm{c} \approx \Omega\gamma_\mathrm{max}^2$

- Power spectrum is flat for $\omega \ll \omega_c$ for constant electric field

(Reville & Kirk 2010)

Summary

- An oscillating model is more realistic for pulsars
- LAE may explain pulsar emissions up to hard X-rays
- LAE is implausible as a γ-ray emission mechanism
- High frequency spectrum not very sensitive to waveform, however, low frequency emission is sensitive
- Future work: detailed investigation of applicability of LAE to to radio emission and also high energy emission

Thank you