Why after 50 years is there no consensus on the pulsar radio emission mechanism?

or

What is the most plausible (= least implausible) amongst suggested emission mechanisms?

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Summary of Talk

- Coherent emission in astrophysics
- Why no consensus? Observations
- Why no consensus? Theory
- Specific emission mechanisms: overview
- Properties of pulsar plasma
- Coherence mechanisms
- Coherent curvature emission (CCE)
- Relativistic plasma emission (RPE)
- Anomalous Doppler emission (ADE)
- Wave dispersion: cold pulsar plasma model
- Effect of relativistic spread in energy ($\langle\gamma\rangle \gg 1$)
- Wave dispersion: conventional pulsar plasma
- Beam-driven RPE revisited
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- Summary and conclusions

Coherent emission in astrophysics

Identification of coherent emission

- Early 1950s: most sources due to synchrotron emission
  incoherent gyromagnetic emission with $\gamma \gg 1$
- => brightness limited by synchrotron (self-) absorption
  => $T_B \lesssim \gamma m_e c^2$ ($1\,\mathrm{MeV} \approx 10^{10}\,\mathrm{K}$)
- exception: solar radio burst with $T_B \gg 10^{10}\,\mathrm{K}$
  => not due to incoherent emission
- Called "coherent emission" = "non-incoherent emission"

Two well-estabilished coherent emission mechanisms

- Plasma emission: emission at $\omega_p, 2\omega_p$ in solar radio bursts
- Electron cyclotron maser emission (ECME): emission at Ω_e from planetary magnetospheres & solar and stellar flares

Pulsar radio emission has extreme $T_B \gtrsim 10^{30}\,\mathrm{K}$

=> must involve some form of coherent emission

Why no consensus? Observations

Observations of pulsar radio emission

- => many "rules" but exceptions to most rules
  What rules are to be regarded as essential?
  Do we emphasize the rules or the exceptions?

Uncertainties

- Is there a single emission mechanism?
  Yes: similarity of emission from three classes of pulsars
  No: difference between core and conal emission
- Location of radio source not known:
  Near the last closed field line? At what height?
- Is the emission mechanism broadband or narrowband?
  Either compatible with radius-to-frequency mapping
- Polarization: rotating vector model => sweep of PA
  jumps between orthogonal modes
  circular polarization; large pulse-to-pulse variation
- Polarization strongly modified by propagation effects

Why no consensus? Theory

Pulsar electrodynamics inadequately understood

- Plasma parameters depend on details of pair creation
- Where are pairs created?
- How is radio emission related to pair creation?
- How inhomogeneous is resulting pulsar plasma?
  Structured along **B** in bunches?
  Structured across **B** implying ducting?

Identification of emission mechanism obscured by:

- Emission by highly relativistic particles
  $=>$ beaming of emission along field lines
  applies to every emission mechanism
- No agreement on coherence mechanism
- Uncertainties concerning wave dispersion in pulsar plasma
- Modifications of emission through propagation effects

Specific emission mechanisms: overview

Classifications of pulsar radio emission mechanisms

- Plasma-emission-like (depend intrinsically on wave dispersion):
  relativistic plasma emission (RPE)
  anomalous Doppler emission (ADE)
- ECME-like (exist in vacuo):
  coherent curvature emission (CCE)
  linear acceleration emission (LAE)
  free-electron maser emission (FEM) (included in LAE)
- Other: emission by oscillating charge sheets,
  possible analogy with emission by EASs in air, ...

Coherence mechanisms (Ginzburg & Zhelezynakov 1975)

- Antenna: pre-existing bunches ("Deo ex machina")
  self-bunching (= reactive or hydrodynamic) instability
  either requires nearly mono-energetic distribution
- Maser: due to negative absorption
  "beam-driven" requires $\partial f(\gamma)/\partial\gamma > 0$
  exception ADE driven by anisotropy $p_\perp = 0$

Properties of pulsar plasma

Pulsar plasma in polar-cap region

- Strong B => 1D, $p_\perp = 0$, no gyration
- Uncertainty: Is stellar surface important source of charge?
- Yes: => "primary" particles: $\gamma \approx 10^6$–10^7
  "secondary" pair plasma (Hibschman & Arons 2001; Arendt & Eilek 2002)
- No: => pair cascade produced without primaries (Timokhin 2010)
- Relativistic pairs streaming outward: $\gamma_s \approx 10^3$?
- Relativistic spread: $\Delta\gamma \approx 10$–10^2?
- Pair multiplicity: $\kappa = n_\pm/(\rho_{\rm cor}/e) \approx 10^5$?

"Conventional" parameters as functions of r/r_L:

$$\frac{\Omega_e}{2\pi} = 3\times 10^7\,\mathrm{Hz}\left(\frac{\dot{P}/P^5}{10^{-15}}\right)^{1/2}\left(\frac{r}{r_L}\right)^{-3}, \qquad \frac{\omega_p}{2\pi} = 7\times 10^3\,\mathrm{Hz}\left(\frac{\kappa}{10^5}\right)^{1/2}\left(\frac{\dot{P}/P^7}{10^{-15}}\right)^{1/4}\left(\frac{r}{r_L}\right)^{-3/2},$$

$$\beta_A^2 = \frac{\Omega_e^2}{\omega_p^2\langle\gamma\rangle} = 30\left(\frac{10}{\langle\gamma\rangle}\right)\left(\frac{10^5}{\kappa}\right)\left(\frac{\dot{P}/P^3}{10^{-15}}\right)^{1/2}\left(\frac{r}{r_L}\right)^{-3}$$

$P = 1\,\mathrm{s}$, $\dot{P} = 10^{-15}$, $r = 0.1 r_L$ => $\Omega_e/2\pi = 30\,\mathrm{GHz}$, $\omega_p/2\pi = 20\,\mathrm{kHz}$, $\beta_A^2 = 3\times 10^4$

Coherent curvature emission (CCE)

Arguments for & against CCE:

Observational features consistent with CE (e.g., Mitra et al. 2009)

Theoretical arguments suggest CCE untenable (Melrose 1980, 1995)

Coherence due to bunches

- Frequency: incoherent CE peaks at $\omega \approx (c/R_c)\gamma^3$
- Problems with assumed emission by bunches:
  - requires mechanism to produce bunching
  - bunch disperses quickly unless nearly mono-energetic
  - inconsistent with expected relativistic spread in γ

Maser curvature emission

- Maser impossible in simplest case (Blandford 1975; Melrose 1978)
- Maser possible when additional effects included (Zheleznyakov & Shaposhnikov 1979; Chugunov & Shaposhnikov 1988; Luo & Melrose 1992, 1995)
- Driven by $\partial f(\gamma)/\partial\gamma > 0 => $ small γ
- No realistic model based on maser curvature emission

My opinion of CCE: untenable

Relativistic plasma emission (RPE)

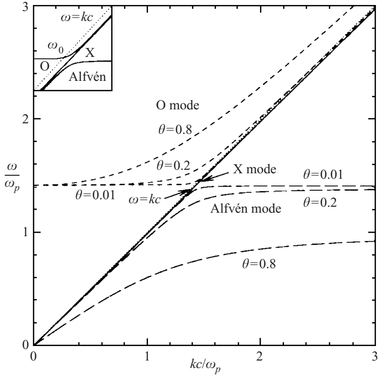
Ongoing arguments in favor of RPE
notably to explain Crab nanoshot (Eilek & Hankins 2016)

Beam-driven Langmuir-like waves

- Beam along **B** at speed $\beta_b c$
- Resonance condition $\beta_\phi = \omega/k_\parallel c = \beta_b => \gamma_\phi = \gamma_b$
  $\gamma_\phi = (1-\beta_\phi^2)^{-1/2}$, $\gamma_b = (1-\beta_b^2)^{-1/2}$
- Early literature: waves assumed to be Langmuir-like, $\omega \approx \omega_p$
- Estimated growth rates too small to be effective
- Inhomogeneous model (Usov 1987; Ursov & Usov 1988)
  faster particles in following beam overtake
  slower particles in preceding beam
- Conversion process a "bottle-neck" (Usov 2000)

Realistic model for dispersion in pulsar plasma
$=>$ no "Langmuir-like waves" with $\beta_\phi < 1$

Beam-driven Alfvén waves



Dispersion relations in the rest frame of cold pulsar plasma (Lyutikov 1999).
Beam-driven waves generated where dispersion curve crosses line $\omega/k_{\|}c = \beta_b$ at an angle $1/\gamma_b$ to the (dotted) light line.

- RPE due to beam driven Alfvén waves
  (Kaplan & Tsytovich 1972; Lominadze et al. 1982; Lyutikov 1999)
- Large growth rate estimated
  => most favorable form of RPE?
- Realistic model for wave dispersion suggests otherwise

Anomalous Doppler emission (ADE)

Instability driven by extreme anisotropy, $p_\perp = 0$

(Machabeli & Usov 1979; Kazbegi et al. 1991; Lyutikov et al. 1999)

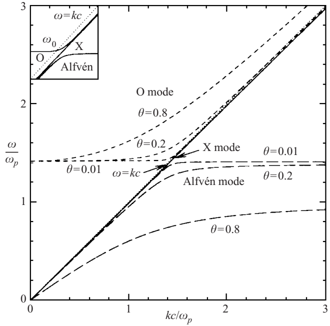
- Resonance condition: $\omega - s\Omega_e/\gamma - k_\parallel v_\parallel = 0, \quad s = -1$
- Requires $\beta > \beta_\phi = \omega/k_\parallel c$ or $\gamma > \gamma_\phi$
- Frequency: $\omega = 2\gamma_\phi^2\Omega_e\gamma/(\gamma^2 - \gamma_\phi^2) \approx 2\gamma_\phi^2\Omega_e/\gamma$
- Example: X or O mode
    - $\gamma_\phi = \beta_A$ with $\beta_A \gg 1$
    - above numbers => $\dfrac{\omega}{2\pi} = \dfrac{10^{15}\,\mathrm{Hz}}{\gamma}\left(\dfrac{\dot{P}/P^4}{10^{-15}}\right)\left(\dfrac{r}{r_L}\right)^{-6}$
    - Observed frequencies require $\gamma = 10^6$–10^7, $r \approx r_L$
    - => higher frequencies for shorter P

My opinion of ADE: Untenable for “conventional” parameters

Wave dispersion: cold pulsar plasma model

Waves in rest frame of cold pulsar plasma

- Cyclotron frequency $\gg$ radio frequencies ($\Omega_e \gg \omega$)
- Cold plasma model in plasma rest frame
  => two wave modes, labeled O and X (Arons & Barnard 1986)
- X-mode dispersion relation $\omega = kc\beta_0$, $\beta_0 \approx 1 + 1/2\beta_A^2$
- L mode $\theta = 0$ crosses Alfvén mode
  reconnection => O-mode and Alfvén for $\theta \neq 0$



Dispersion curves in rest frame of cold pulsar plasma (Lyutikov 1999).
Relativistic dispersion modifies O and Alfvén mode
X mode unchanged.
Cold-plasma model misleading: resonance in Alfvén mode artefact

Effect of relativistic spread in energy ($\langle\gamma\rangle \gg 1$)

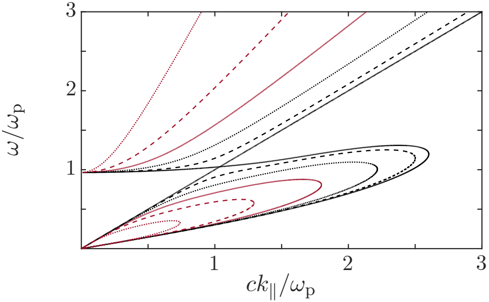
Dispersion in pulsar plasma

- Dispersive properties in 1D pair plasma studied since 1970s
  implications still not widely recognized
- Relativistic streaming: $\gamma_\mathrm{s} \gg 1$ in pulsar frame
  removed by Lorentz transform to plasma rest frame
- Two essential parameters: $\langle\gamma\rangle \sim 10$–$100$, $\beta_A \gg 1$
- Dispersion not sensitive to choice of $f(\gamma)$ (Melrose & Gedalin 1999)

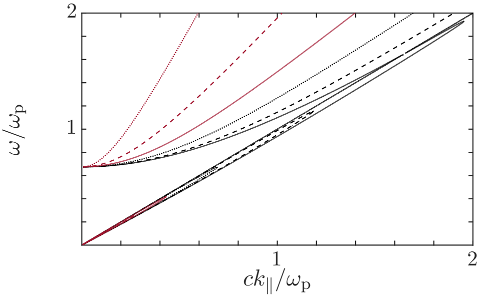
Plots of dispersion relations

- 1D Jüttner: $f(\gamma) \propto e^{-\rho\gamma}$, $\rho = mc^2/T$
  nonrelativistic $\rho = c^2/V^2 \gg 1 \rightarrow$ relativistic $\rho = 1/\langle\gamma\rangle \ll 1$
- Plots ω vs $k_\parallel c$, diagonal $\beta_\phi = \omega/k_\parallel c = 1$
  => resonance $\beta = \beta_\phi$ possible only below diagonal
- X mode insensitive to ρ: $n_\mathrm{X} = 1/\beta_0 \approx 1 + 1/2\beta_A^2$
  not included in plots shown here

Examples: $\rho = 20$ **and** $\rho = 1$



Dispersion curves:
$\rho = 20$, $\beta_A \gg 1$
LO mode (upper)
Alfvén mode (lower)
curves: $\theta = 0$ (solid) &
$\theta = n \times 0.25$, $n = 1$–5
Landau damping strong
below turnover.



Dispersion curves:
$\rho = 1$, $\beta_A \gg 1$
Alfvén mode:
maximum $\omega \downarrow$ as $\theta \uparrow$
maximum along line
$\omega/k_\parallel c \approx 1 - \delta$,
maybe $\delta \approx 1/\langle\gamma\rangle^2$?

Wave dispersion: conventional pulsar plasma

X mode vacuum-like for all $\langle\gamma\rangle$: $\omega = kc\beta_0$, $\beta_0 \approx 1 + 1/2\beta_A^2$
Only LO mode & Alfvén mode need comment

Parallel propagation

- Distinct L & A modes
- L mode cutoff ($k_\parallel = 0$): $\omega_c = \omega_p \langle\gamma^{-3}\rangle^{1/2}$
- Crosses $\omega = k_\parallel c$ at $\omega_1 \approx \omega_p \langle\gamma\rangle^{1/2}$
  $\omega > k_\parallel c$ in range $\omega_c < \omega < \omega_1$
  $\omega < k_\parallel c$ in tiny range $\omega_1 < \omega < \omega_{\max}$
- A and X mode degenerate with opposite transverse polns

Oblique propagation

- L & A modes reconnect => LO mode & oblique Alfvén mode
- $\theta\uparrow$ => LO mode moves to left => $\beta_\phi > 1$
  => no resonance possible
- $\theta\uparrow$ => Alfvén mode to $\omega\downarrow$ (at $\beta_\phi \approx 1 - 1/\langle\gamma\rangle^2$?)
  => beam resonance requires $\gamma_b \gg \langle\gamma\rangle$

Beam-driven RPE revisited

RPE in LO mode

- Resonance possible for LO mode for $\gamma_b > \beta_A$
  but only for tiny range of $\theta \approx 0$
- LO mode waves can escape freely (no "bottle-neck")
  but small growth rate + short growth time
  => not a realistic emission mechanism

RPE in Alfvén mode

- Resonance possible for $\gamma_b \gg \langle\gamma\rangle$ in rest frame
- Existing models have not treated dispersion accurately
- Problem with inadequate growth rate remains
- Problem with conversion "bottle-neck" remains

My opinion: "least unlikely" suggested emission mechanisms
but: no beam-driven RPE seems plausible

Rotation-driven RPE

A non-beam-driven version of RPE seems most favorable

Rotation-driven RPE

- Oblique rotator => $E_{\parallel}$, screening by charges unstable
  => large-amplitude oscillations (LAOs) in $E_{\parallel}$
  (Levinson et al. 2005; Belobodorov & Thompson 2007)
- Interpretation: rotational energy drives LAOs through $E_{\parallel}$
- LAOs have $1 < \beta_\phi < \infty$ (not beam-driven)
  $\omega_p/\langle\gamma\rangle^{1/2} < \omega < \omega_p\langle\gamma\rangle^{1/2}$
- Alternative source of LAOs: rotational pumping
  => parametric instability (Machabeli & Rogava 1994; Machabeli et al. 2005)
- Consistent with abrupt slowing down (Kramer et al. 2006; Lyne et al. 2010)

Conversion into escaping radiation

- Acceleration by $E_{\parallel}$ to $\gamma \gg 1$ in LAO => LAE
- Maser LAE produces escaping radiation
  (Melrose 1978; Melrose et al. 2009; Reville & Kirk 2010)
- Maser driven by $\partial f(\gamma)/\partial\gamma > 0$ => $\gamma \lesssim \langle\gamma\rangle$, e.g. $\gamma \lesssim 10$?

My opinion: A detailed model needs to be developed

Summary and conclusions

- Observations: many rules with many exceptions
  => ambiguous constraints on emission mechanism
- Theory: Pulsar electrodynamics inadequately understood
  no specific emission mechanism favored
- Coherent curvature emission (CCE):
  dubious coherence mechanism
- Relativistic plasma emission (RPE):
  no beam-driven "Langmuir-like" waves
  beam-driven Alfvén waves problematic
- Anomalous Doppler emission (ADE):
  implausible with conventional parameters
- More realistic alternative needed:
  Rotation-driven LAOs implied by electrodynamics
  Maser LAE => escaping radiation
  no detailed model exists
- Another alternative approach:
  analogy with coherent emission in extensive air showers?