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)
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- Wave dispersion: cold pulsar plasma model
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- Wave dispersion: conventional pulsar plasma
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Coherent emission in astrophysics

Identification of coherent emission

- Early 1950s: most sources due to synchrotron emission
  incoherent gyromagnetic emission with $\gamma \gg 1$

- $\Rightarrow$ brightness limited by synchrotron (self-) absorption
  $\Rightarrow T_B \lesssim \gamma m_e c^2$ (1 MeV $\approx 10^{10}$ K)

- exception: solar radio burst with $T_B \gg 10^{10}$ K
  $\Rightarrow$ not due to incoherent emission

- Called “coherent emission” = “non-incoherent emission”

Two well-established coherent emission mechanisms

- Plasma emission: emission at $\omega_p, 2\omega_p$ in solar radio bursts

- Electron cyclotron maser emission (ECME): emission at $\Omega_e$
  from planetary magnetospheres & solar and stellar flares

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

$\Rightarrow$ 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 $\mathbf{B}$ in bunches?
  Structured across $\mathbf{B}$ implying ducting?

**Identification of emission mechanism obscured by:**

- Emission by highly relativistic particles
  \[\Rightarrow\] 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 $B \Rightarrow 1D$, $p_\perp = 0$, no gyration
- Uncertainty: Is stellar surface important source of charge?
- Yes: $\Rightarrow$ “primary” particles: $\gamma \approx 10^6–10^7$
  “secondary” pair plasma (Hibschman & Arons 2001; Arendt & Eilek 2002)
- No: $\Rightarrow$ 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: $\kappa = n_\pm/(\rho_{\text{cor}}/e) \approx 10^5$?

“Conventional” parameters as functions of $r/r_L$:

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

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

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

Maser curvature emission

- Maser impossible in simplest case (Blandford 1975; Melrose 1978)
- Maser possible when additional effects included
  - Driven by $\partial f(\gamma)/\partial \gamma > 0 \Rightarrow$ small $\gamma$
  - 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 $\mathbf{B}$ at speed $\beta_b c$
- Resonance condition $\beta_\phi = \omega / k_\parallel c = \beta_b \Rightarrow \gamma_\phi = \gamma_b$
  \[
  \gamma_\phi = (1 - \beta_\phi^2)^{-1/2}, \quad \gamma_b = (1 - \beta_b^2)^{-1/2}
  \]
- 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
  $\Rightarrow$ 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 $\omega / k \parallel c = \beta_b$ 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**
  $\Rightarrow$ 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: \( \omega - s\Omega_e/\gamma - k_\| v_\| = 0, \quad s = -1 \)
- Requires \( \beta > \beta_\phi = \omega/k_\| c \) 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 \( \Rightarrow \frac{\omega}{2\pi} = \frac{10^{15}}{\gamma} \left( \frac{\dot{P}/P^4}{10^{-15}} \right) \left( \frac{r}{r_L} \right)^{-6} \)
  - Observed frequencies require \( \gamma = 10^6-10^7, \quad r \approx r_L \)
  - \( \Rightarrow \) 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
  $\Rightarrow$ 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 $\Rightarrow$ 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: $\gamma_s \gg 1$ 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 $\omega$ vs $k_\parallel c$, diagonal $\beta_\phi = \omega / k_\parallel c = 1$
  $\Rightarrow$ resonance $\beta = \beta_\phi$ possible only below diagonal
- X mode insensitive to $\rho$: $n_X = 1/\beta_0 \approx 1 + 1/2\beta_A^2$
  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 $\langle \gamma \rangle$: $\omega = kc\beta_0$, $\beta_0 \approx 1 + 1/2\beta^2_A$

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 $\omega_1 < \omega < \omega_{\text{max}}$
- A and X mode degenerate with opposite transverse polns

Oblique propagation

- L & A modes reconnect $\Rightarrow$ LO mode & oblique Alfvén mode
- $\theta \uparrow \Rightarrow$ LO mode moves to left $\Rightarrow \beta_\phi > 1$
  $\Rightarrow$ no resonance possible
- $\theta \uparrow \Rightarrow$ Alfvén mode to $\omega \downarrow$ (at $\beta_\phi \approx 1 - 1/\langle \gamma \rangle^2$?)
  $\Rightarrow$ 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
  $\Rightarrow$ 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 $\Rightarrow E_\parallel$, screening by charges unstable
  $\Rightarrow$ 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
  $\Rightarrow$ 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 $\Rightarrow$ LAE
- Maser LAE produces escaping radiation
  (Melrose 1978; Melrose et al. 2009; Reville & Kirk 2010)
- Maser driven by $\partial f(\gamma)/\partial \gamma > 0 \Rightarrow \gamma \lesssim \langle \gamma \rangle$, 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?