Radio emission theories of pulsars

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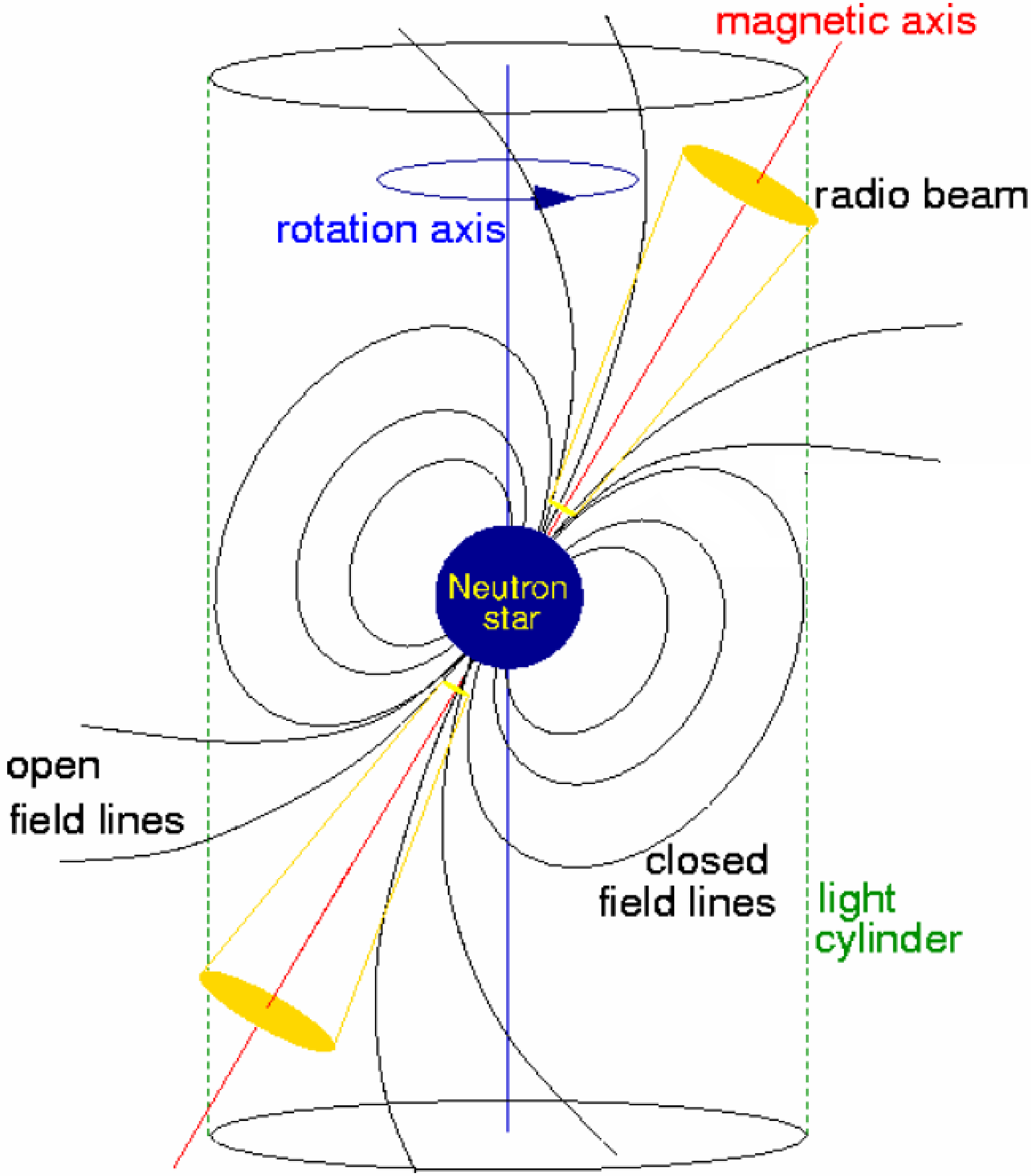
magnetic axis
radio beam
rotation axis
Neutron star
open field lines
closed field lines
light cylinder

Theoretical conceptions before discovery of pulsars

- **Neutron stars**
  *(Baade **&** Zwicke**, Proc. Natl. Acad. Sci. U.S.A.pJ, 20,** 254**,** 1934)*

- **Strong magnetic fields**
  *(Ginzburg**, Sov. Phys.- Dokl, 156,** 43**,** 1964; Waltjer, **ApJ, 140,** 1309**,** 1964)*

- **Deceleration of rotation of neutron stars by strong magnetic fields and the rotational energy release**
  *(Pacini**, Nature, 221,** 567**,** 1967)*

The rotational energy losses of neutron stars → **The non-thermal radiation of pulsars**

The rotational energy of neutron stars is $E_{rot} = \frac{1}{2} I\Omega^2.$

$$L_{rot} = -\frac{dE_{rot}}{dt} = -I\Omega\dot{\Omega} \sim 10^{30} - 10^{38}\, ergs/s$$

$L_{rot} > L_{non-th}$ *for all known pulsars*

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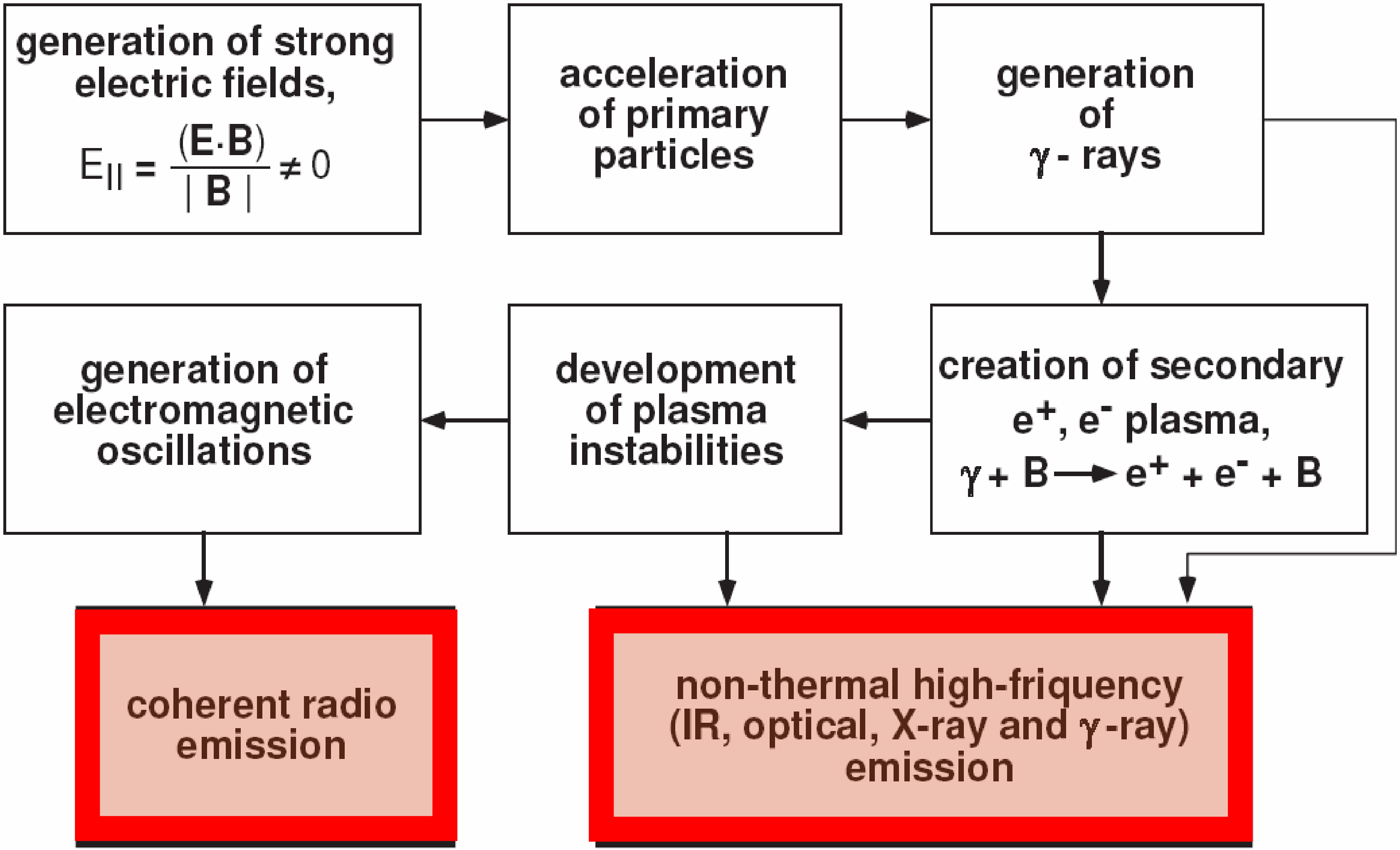
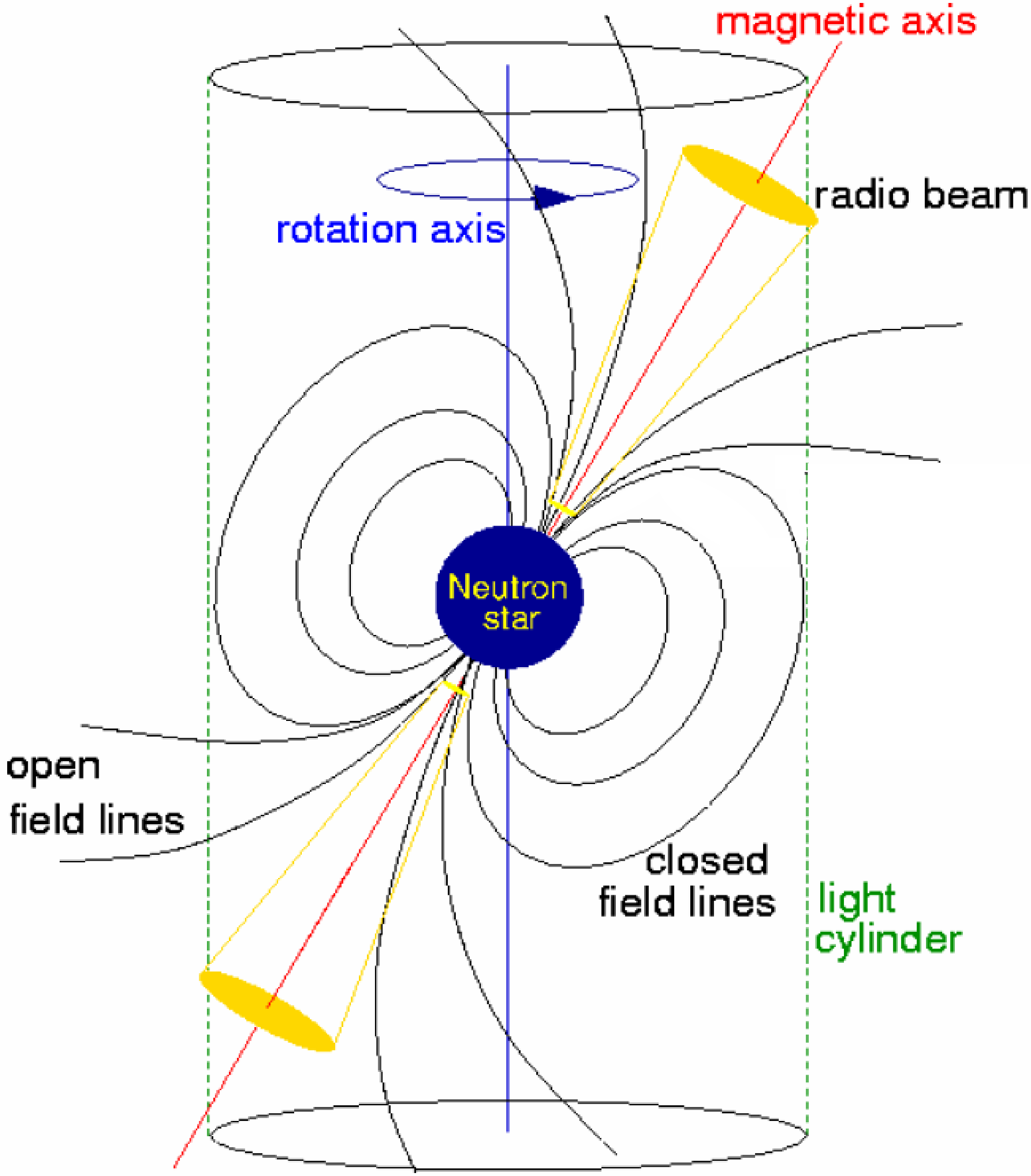
Physical processes in pulsar magnetospheres

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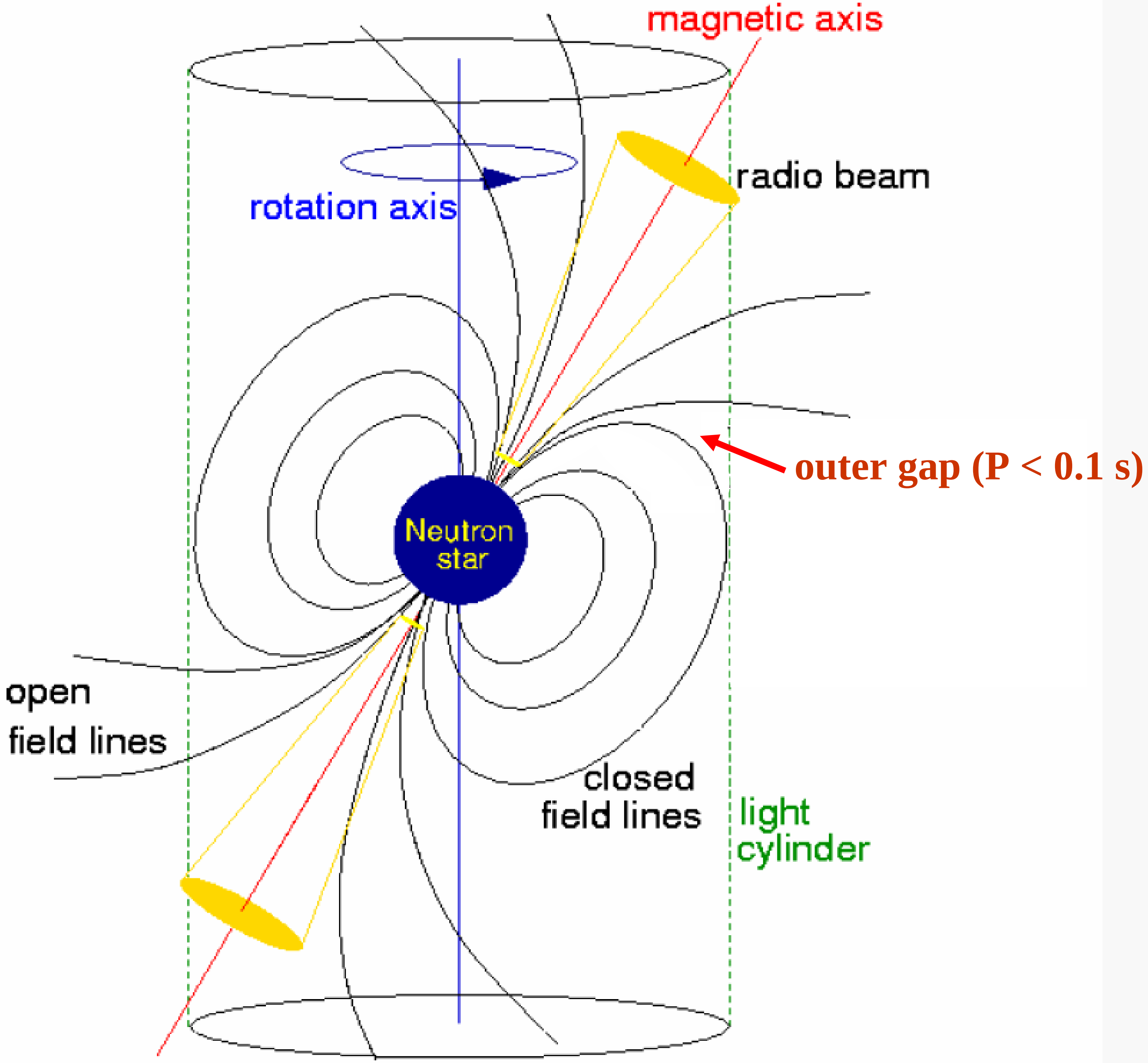
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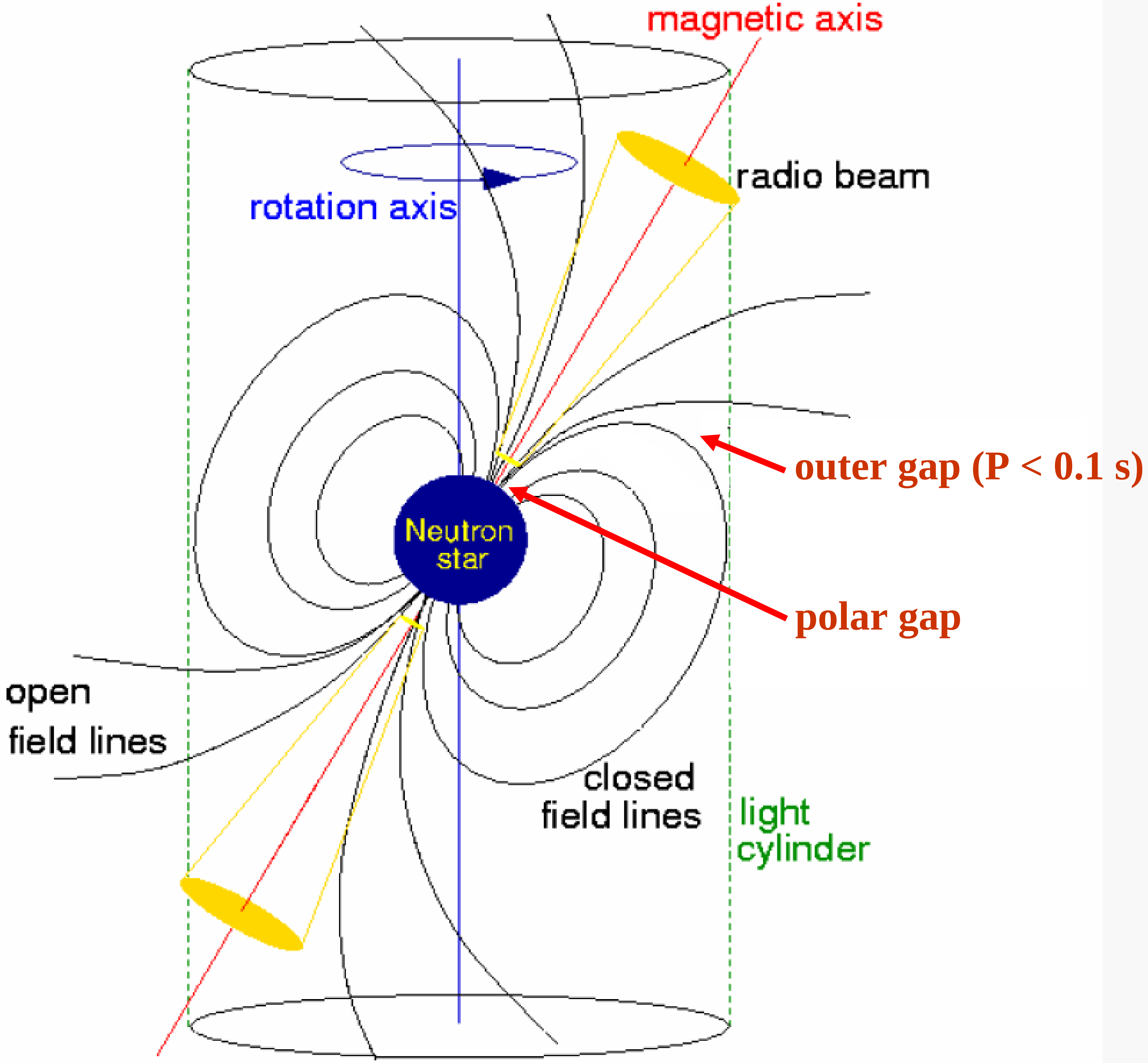
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PULSARS (PSRs)

Normal PSRs

$P \simeq 0.1 - 8$ s

$B_P \simeq 10^{11} - 10^{14} G$

Polar gap

Millisecond PSRs

$P \simeq 1 - 10$ ms

$B_P \simeq 10^{9} - 10^{10} G$

?

Young PSRs

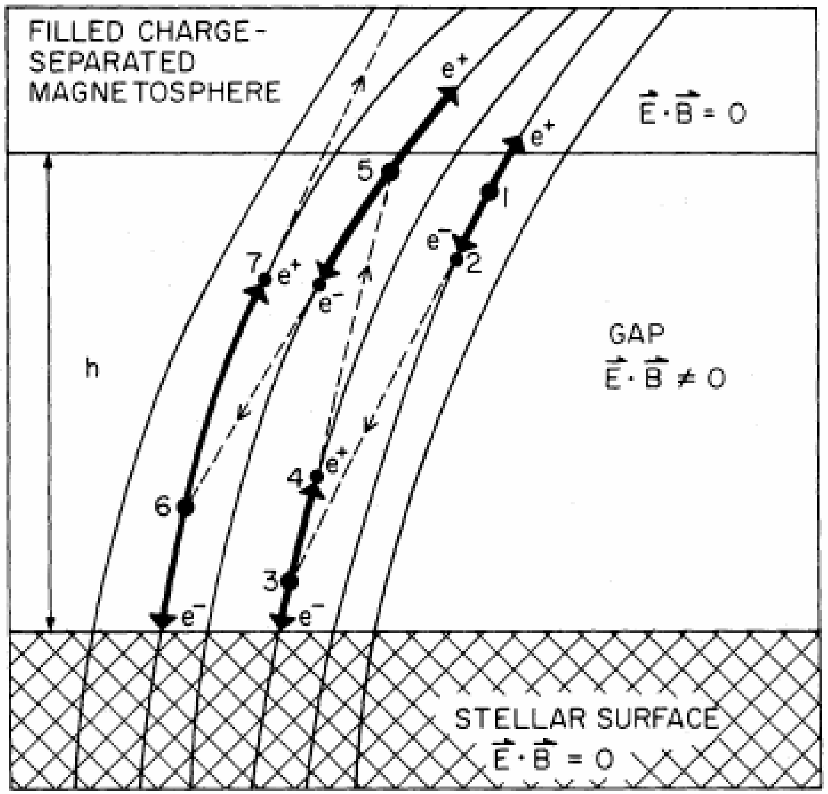
$P \simeq 0.033 - 0.1$ s

$B_P \simeq 10^{12} - 10^{13} G$

Outer gap

The polar gap model

$$\Phi_{max} \simeq \left(\frac{\Omega R}{c}\right)^2 B_p R \simeq 10^{13}\left(\frac{B_p}{10^{12} G}\right)\left(\frac{P}{1\ s}\right)^{-2} \mathrm{V}$$



Breakdown of the polar gap. The solid lines are polar field lines of average radius of curvature ρ; for a pure dipole field $\rho \sim (Rc/\Omega)^{1/2} \sim 10^8 P^{1/2}$ cm, but for a realistic pulsar one expects $\rho \sim 10^6$ cm if many multipoles contribute near the surface.

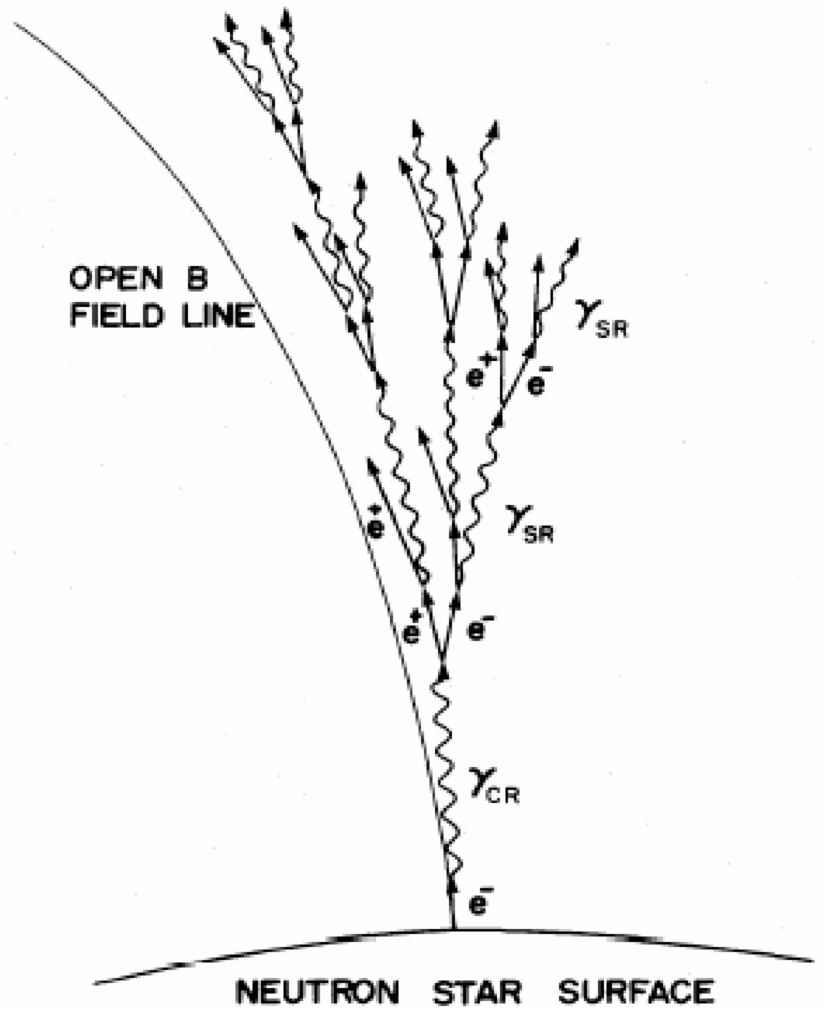
The boundary condition for $\vec{E}$ at the neutron star surface may differ.

$\vec{E}_{\parallel} = \frac{\vec{E}\cdot\vec{B}}{B^2}\vec{B} = 0$ for Arons-type models, in which particles flow freely from the surface, $h \simeq 10^5 - 10^6$ cm.

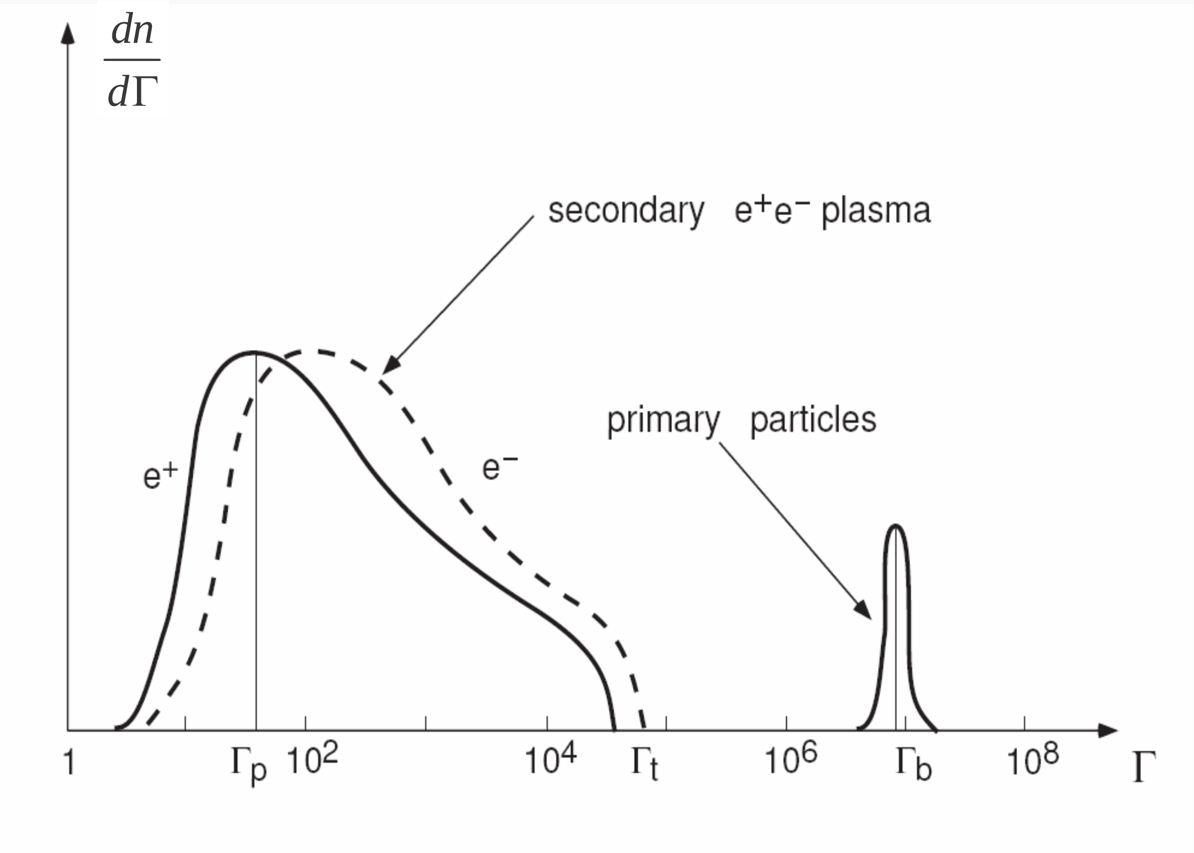
$\vec{E}_{\parallel} \neq 0$ for Ruderman-Sutherland-type models, in which particles are tightly bound to the surface, $h \simeq 10^3 - 10^4$ cm.

$$\Phi \simeq 10^{12} - 10^{13}\ \mathrm{V}$$

Electromagnetic cascades (*Daugherty* **&** *Harding*, ***ApJ***, **252**, *337*, *1982*)



Schematic representation of a pair photon cascade initiated by an accelerated electron above the polar cap of a pulsar. Four generations of photons, including both curvature radiation photons, γ_{CR}, and synchrotron radiation photons, γ_{SR}, are shown.



$$\Gamma_b \simeq \frac{e\,\Phi}{m_e c^2} \sim 10^6 - 10^7,$$

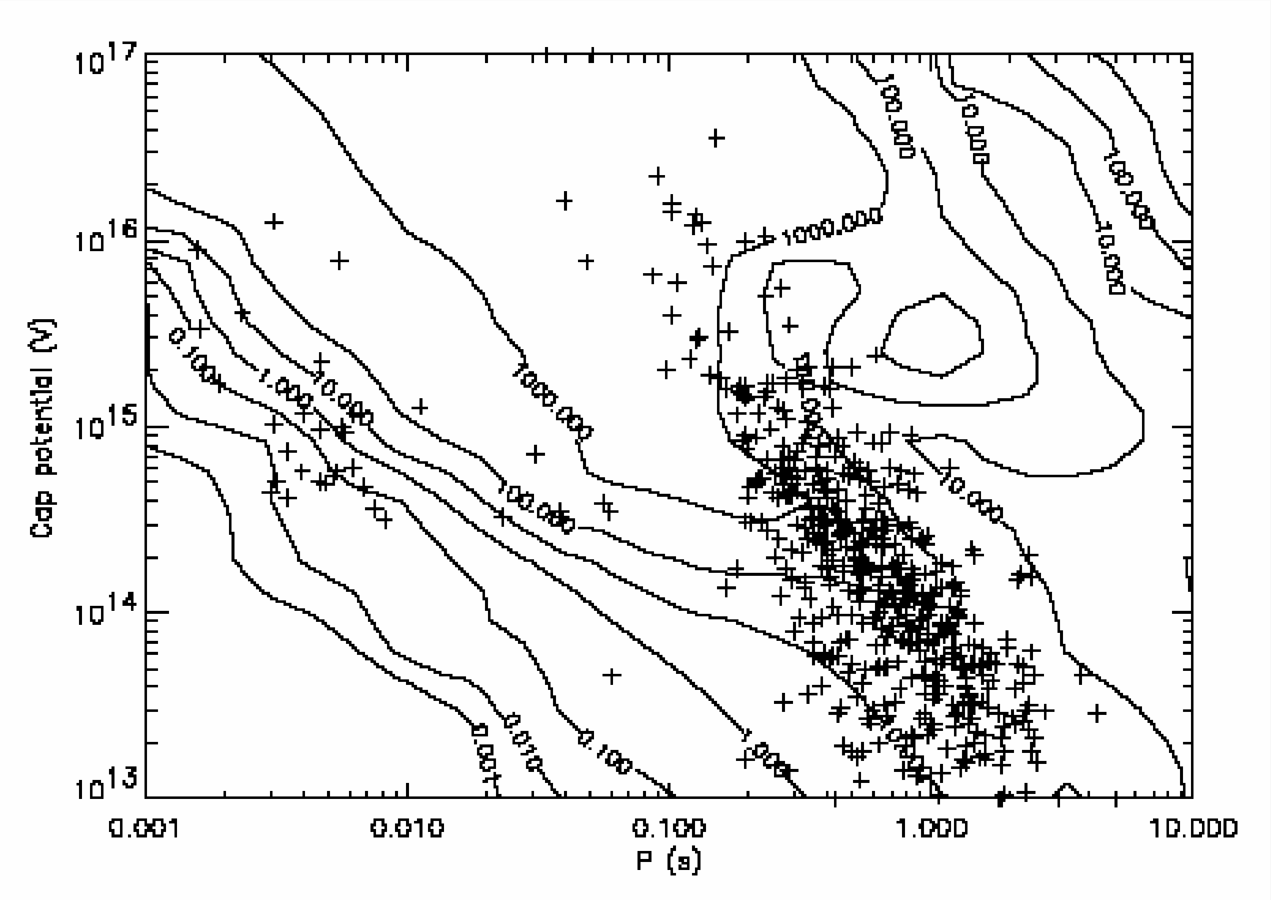
$$\Gamma_p \simeq 10\frac{\rho}{R} \sim 10 - 10^3,$$

$$\Gamma_t \simeq \frac{\bar{\varepsilon}_\gamma}{2m_e c^2} \sim 10^3 - 10^5,$$

$$n_b \simeq n_{GJ} = \frac{\vec{\Omega}\cdot\vec{B}}{2\pi c e} \simeq 7\times 10^{10}\,\frac{B_z}{10^{12}G}\left(\frac{P}{1\ s}\right)^{-1} cm^{-3},$$

$$n_p = \xi\, n_b, \qquad \xi \simeq \frac{\Gamma_b}{\Gamma_p} \sim 10^3 - 10^4.$$

Pair multiplicity, ξ (*Hibschman* **&** *Arons*, ***ApJ*****, 560,** *871*, *2001*)

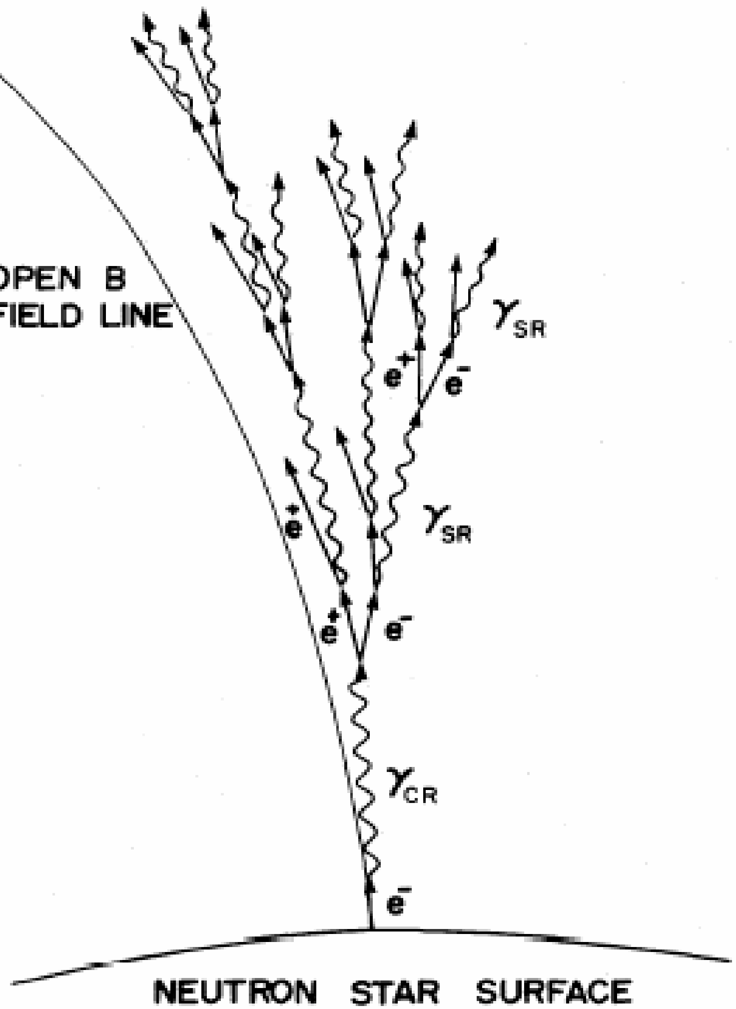


$$\xi \simeq 10 - 10^3$$

$$\tau_s \simeq 10^{-15}\left(\frac{B}{10^{12}G}\right)^{-2}\Gamma\ s \ll \tau_{esc} = \frac{R}{c} \simeq 3\times10^{-5}\ s.$$

The out-flowing plasma is one-dimensional, relativistic and multi-component.

Electromagnetic cascades (*Daugherty* & *Harding*, ***ApJ***, **252**, *337*, *1982*)



Schematic representation of a pair photon cascade initiated by an accelerated electron above the polar cap of a pulsar. Four generations of photons, including both curvature radiation photons, γ_{CR}, and synchrotron radiation photons, γ_{SR}, are shown.

Pulsars with very strong magnetic fields $\left(B_p > 0.1\ B_{cr},\ B_{cr} = \frac{m_e c^3}{e\hbar} \simeq 4.4\times10^{13}\ G\right)$

- $0.1\ B_{cr} < B_p^d < 2\ B_{cr}$ for ~ 10% of PSRs *(Manchester et al.,* ***Astron. J*****, 129,** *1993, 2005).*
- For $B > 0.1\ B_{cr}$, γ-gamma emitted almost tangentially to $\vec{B}$ are captured near the threshold of bound pair creation and are channeled along $\vec{B}$ as bound e^+e^- pairs (positronium) *(Shabad & Usov,* ***ApSS*****, 117,** *309, 1985;* ***128,*** *377, 1986; Usov & Melrose,* ***Aust. J. Phys.*****, 48,** *571, 1995).*

$$\Downarrow$$

Bound pairs do not screen electric fields, and the energy flux in highly relativistic particles from the polar gaps (especially RS-type) increases *(Usov & Melrose,* ***ApJ*****, 464,** *306, 1996; Shabad & Usov, in preparation).*

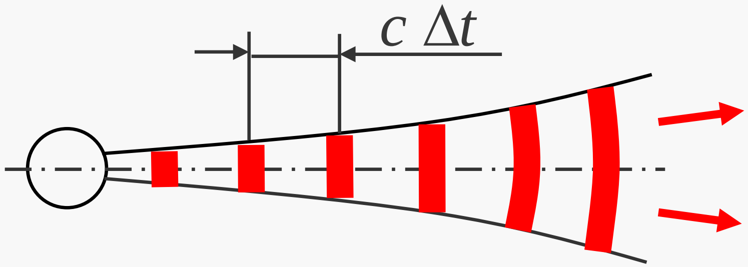
$$\Downarrow$$

Non-thermal radiation from PSRs with $B_p > 0.1\ B_{cr}$ may increases.

- Bound pairs are free from the distance where $B \sim \alpha^2\ B_{cr} \simeq 2.35\times10^9\ G.$

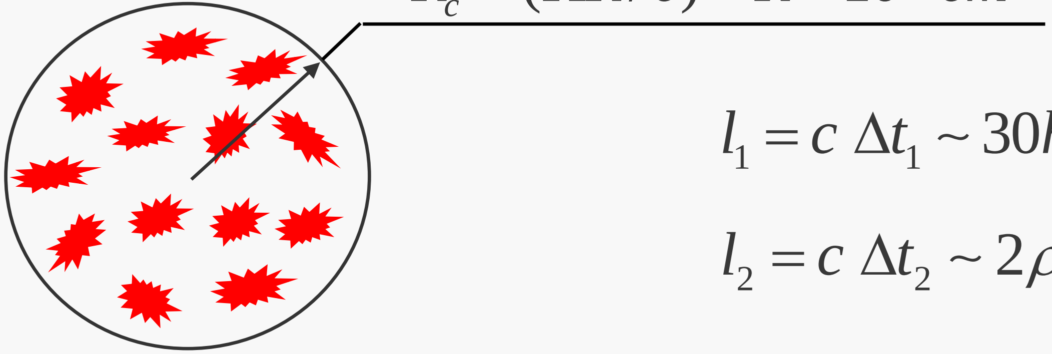
Is the plasma outflow stationary ?

- The pair creation process is non-stationary, first suggestion *(Sturrock*, ***ApJ*, 164,** *529***,** *1971)*



- Non-stationary pair creation in the RS polar gap
(*Ruderman* **&** *Sutherland***,** ***ApJ*, 196,** *51***,** *1975; Beskin*, ***Sov*. *Astron*.**, **26**, *443*, *1982)*

$$R_c \simeq (\Omega R/c)^{1/2} R \sim 10^4 \ cm$$



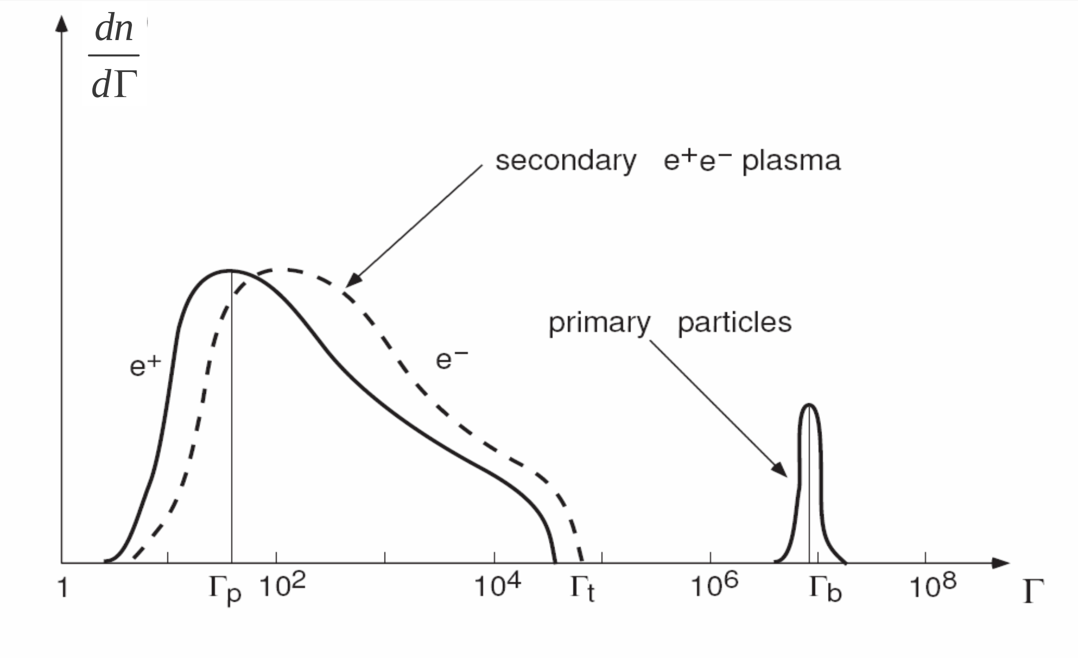
$$l_1 = c\,\Delta t_1 \sim 30h \sim 10^5 \ cm$$

$$l_2 = c\,\Delta t_2 \sim 2\rho \sim 10^7 \ cm$$

The $\vec{E} \times \vec{B}$ drift of spark plasma filaments provides a plausible mechanism explaining the subpulse drift phenomenon *(Gil et al.*, ***A&A*, 407,** *315***,** *2003***)**

- Numerical time-dependent simulations for pair creation
(Alber et at., ***Astrophysics***, **11**, *189*, *1975; Levinson et al***.,** ***ApJ*, 631,** *456***,** *2005***)**

Conclusion



The out-flowing plasma is

- **multi-component,**
- **relativistic,**
- **one-dimensional,**
- **strongly magnetized,**
- **not-uniform, and maybe,**
- **stationary or not.**

For PSRs with $B_p > 0.1\ B_{cr}$ **created pairs are bound in the neutron star vicinity while at large distances,** $r > (2-4)\times 10R,$ **these pairs are free.**

Normal modes in pulsar plasmas

Early studies:

- *Tsytovitch* **&** *Kaplan* (***Astrophysics*, 8,** *260*, *1972*) derived the dispersion relation for a one-dimensional electron gas with a power-law distribution function for $B = \infty$.

- *Godfrey et al.* (***Phys. Fluids*, 18,** *346*, *1975*) considered a cold relativistic electron beam propagating parallel to $\vec{B}$ and through a cold plasma. The dispersion relation was solved both analytically and numerically.

- *Melrose* **&** *Stoneham* (***Proc. Astr. Soc. Austr*, 8,** *260*, *1977*) included quantum effects and dispersion relations are evaluated in the "low-density" limit.

- *Cheng* **&** *Ruderman* (***ApJ*, 229,** *348*, *1979*); *Melrose* (***Austr. J. Phys.*, 32,** *61*, *1979)* discussed the normal modes in a pulsar plasma to explain the formation of the orthogonal radiation modes observed in pulsar radio emission.

Latter-day studies:

Arons **&** *Barnard*, ***ApJ*, 302,** *120*, *1986*; *Lominadze et al.*, ***Sov. J. Plasma Phys.*, 12,** *712*, *1986; Lyutikov*, ***MNRAS*, 293,** *447*, *1998; Lyutikov et al.*, ***MNRAS*, 305,** *338*, *1999; Melrose* **&** *Gedalin*, ***ApJ*, 521,** *351*, *1999; Petrova*, ***A&A*, 408,** *883*, *2001;*

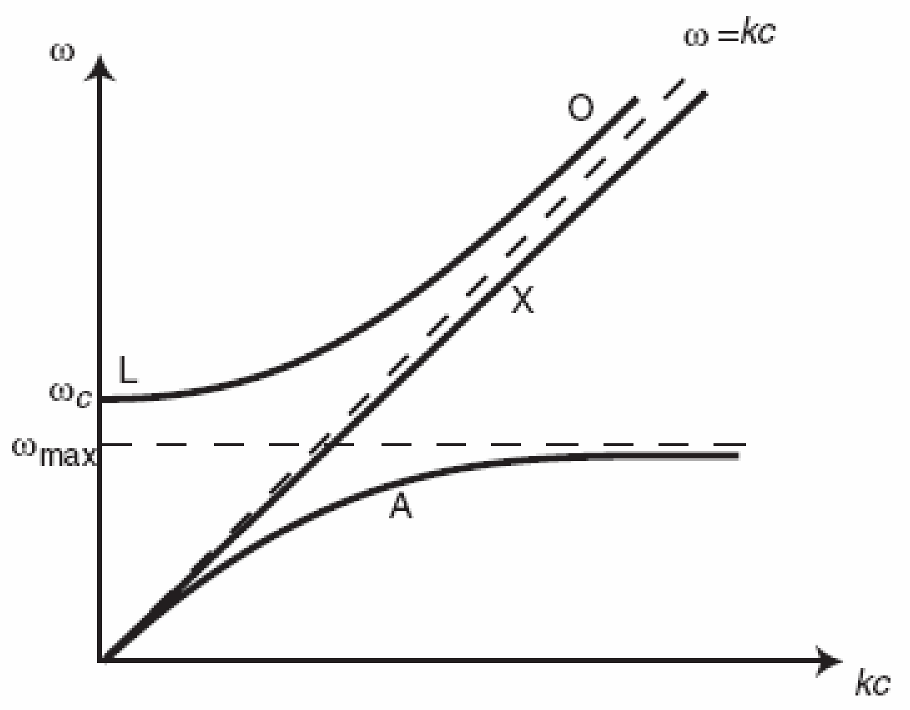
Conventional simplifying approximations:

- $r \geq R \gg \lambda = c/\nu, \quad \Delta t_i \gg \nu^{-1}$ $\Longrightarrow$ plasma is uniform and stationary,
- plasma consists of electrons and positrons with identical spectra (no gyrotropy),
- quantum effects are ignored in treating the pulsar plasma dispersion.

Studies beyond the last two approximations:

Kennet et al., ***J. Plasma Phys.*, 64,** *333*, *2000; Gedalin et al.*, ***MNRAS*, 325,** *715*, *2001; Luo, Melrose*, **&** *Fussell*, ***Phys. Rev. E*, 66,** *026405*, *2002; Melrose*, ***Plasma Phys. Cont. Fus.*, 45,** *523*, *2003.*

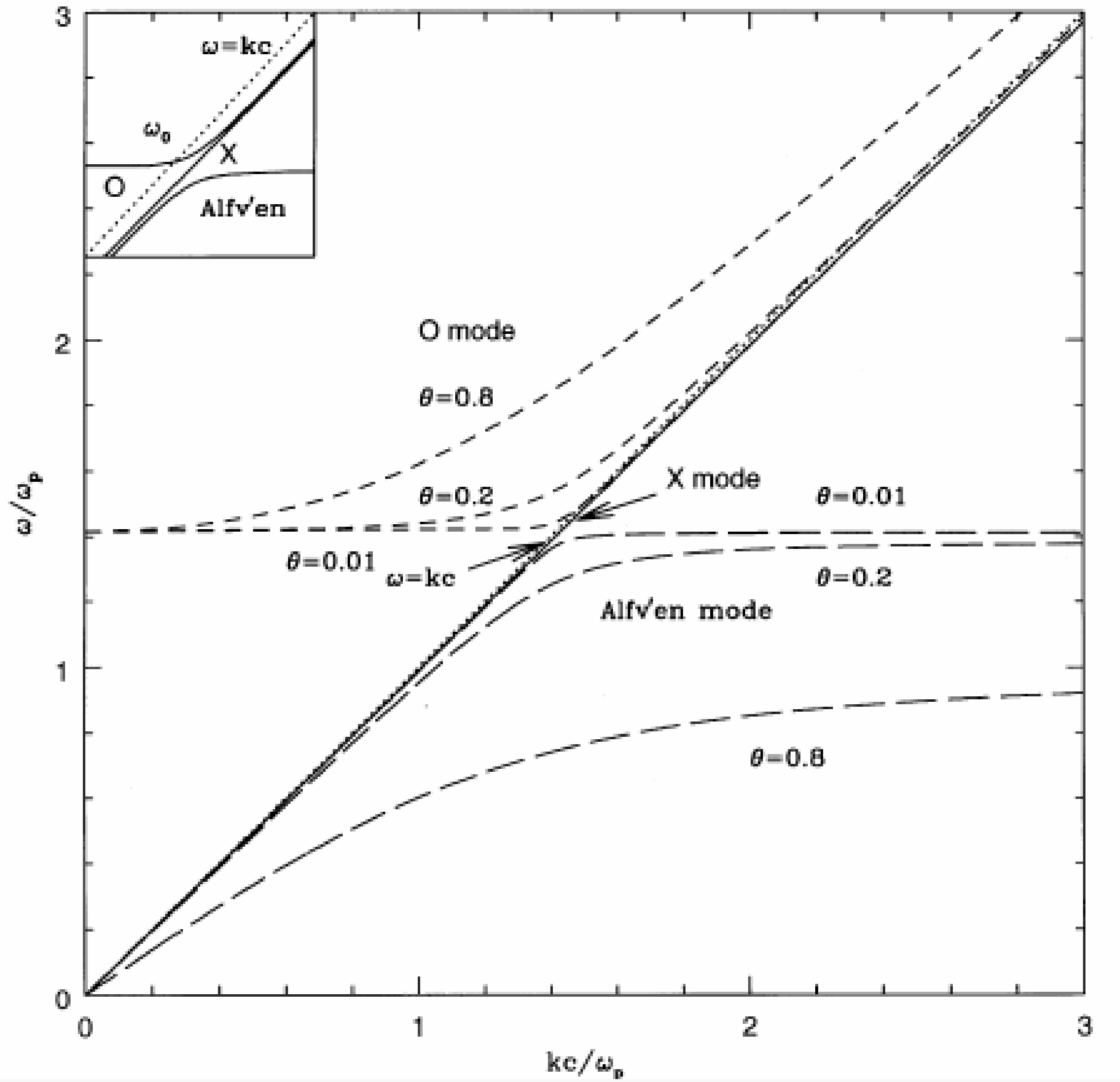
Fundamental plasma modes



The transverse extraordinary mode *(variously known as the X-mode, t-mode, and the fast magnetosonic mode) with the electric field (polarization vector) perpendicular to the* $\vec{k}$-$\vec{B}$ *plane.*

The longitudinal-transverse mode *with the electric field in the* $\vec{k}$-$\vec{B}$ *plane with two branches: the ordinary (O) mode and Alfven (A) mode.*

Dispersion curves for a (non-gyrotropic) pulsar plasma *at frequencies well below the cyclotron frequency for a slightly oblique angle of propagation. The A mode has a maximum frequency,* $\omega_{\rm max}$ *, and is heavily damped as this frequency is approached. The L-O mode is approximately langitudinal (L) near its cut-off,* $\omega_{\rm c} = \omega_p \langle \Gamma^{-3} \rangle^{1/2}$ *(the "relativistic plasma frequency"), and approximately transverse (O) at higher frequencies, where* $\omega_p = (4\pi e^2 n_p / m_e)^{1/2}$ *(Melrose,* ***Plasma Phys. Cont. Fus., 45,*** *523, 2003),*



$$\omega_X = kc\,(1-\delta), \quad \delta = \frac{\omega_p^2\,\Gamma_T}{4\omega_B^2\,\Gamma_p^{\,3}},$$

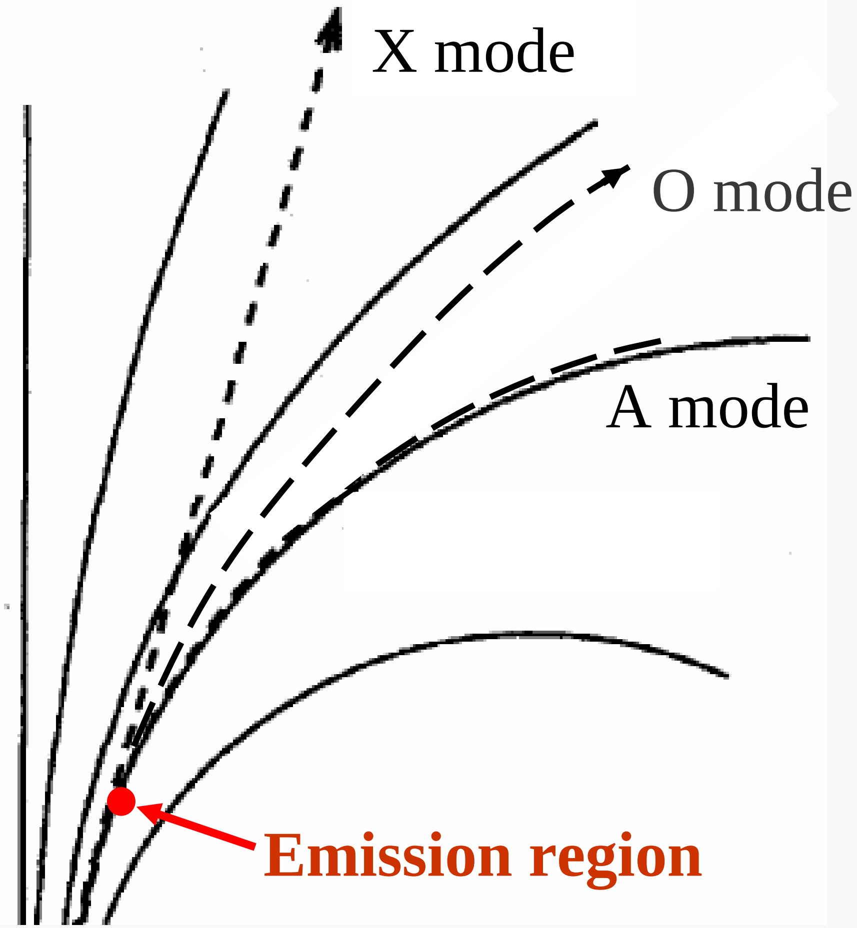
$$\delta \sim 10^{-20} - 10^{-17} \ at\ r \simeq R\,,$$

$$\delta \sim 10^{-6} - 10^{-3} \ at\ r \simeq c/\Omega\,,$$

$$\delta \ll 1\,, \quad \omega_X \simeq kc\,.$$

Dispersion curves for the waves in a cold pair plasma in the plasma frame in the limit $\omega_p \ll \omega_{\rm B}$. *The inset in the upper left corner shows the region near the cross point (Lyutikov, Blandford, and Machabeli,* ***MNRAS*****, 305,** *338, 1999).*

Propagation of normal modes in pulsar magnetospheres



Refractive indices:

$n_X = kc/\omega_X \simeq 1$, *i.e.*,

X mode propagates along a straight line in the direction of $\vec{k}$.

$n_A = kc/\omega_A \simeq (Cos\ \vartheta)^{-1}$.

A-mode propagates along $\vec{B}$.

(Barnard **&** *Arons,* ***ApJ*****, 302,** *138, 1986; Petrova,* ***A&A*****, 360,** *592, 2000; Luo,* ***Publ. Astron. Soc. Aust.*****, 18,** *400, 2001)*

Some properties of normal modes

- X mode with $\vec{e} \parallel \vec{k} \times \vec{B}$ cannot effectively interact with particles moving strictly along $\vec{B}$ through Cherenkov resonance.

- X mode waves may be produces either through cyclotron instability or some nonlinear processes.

- X mode is not Landau damped, and it can be damped through cyclotron resonance.

- LO mode can interact with particles through Cherenkov resonance provided that the parallel phase velocity is less than c.

- The subluminous O waves cannot escape the pulsar magnetosphere because of Landau damping while the superluminous O waves can do this.

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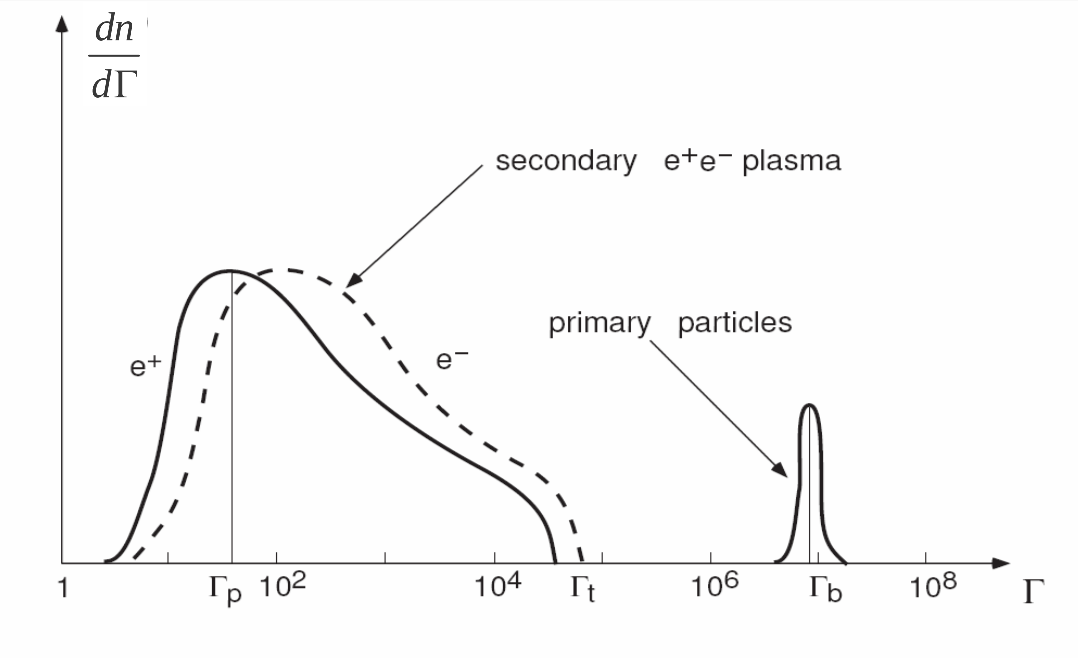

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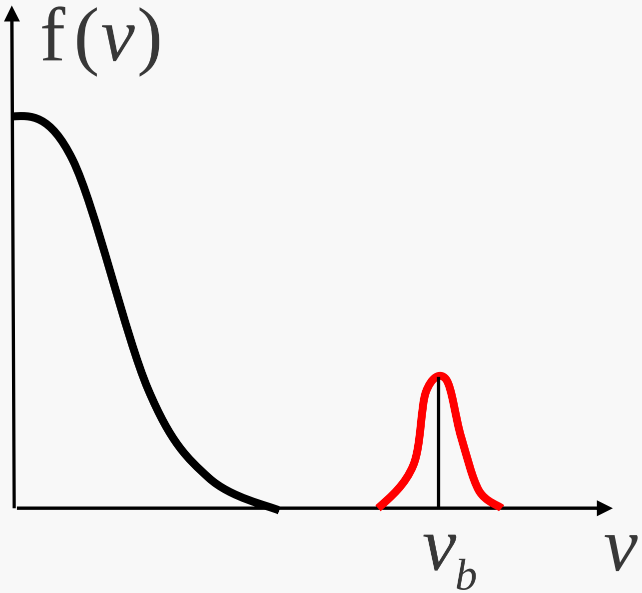
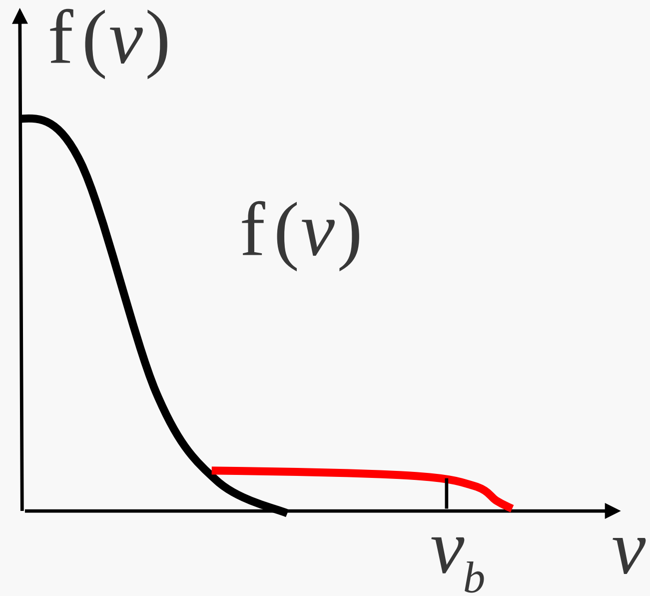
Two-stream instability in pulsar magnetospheres

$\Leftarrow \quad n_2, \quad v_2$

$n_1, \quad v_1 \quad \Rightarrow$

$n_1 \gg n_2,$





$$\mu = -\frac{(2\pi)^2 e^2 v_{ph}^3}{3\omega m_e v_{th}^2} \frac{df(v_{\vec{k}})}{dv_{\vec{k}}} \Bigg|_{v_{\vec{k}} = v_{ph}},$$

$$v_{ph} = \omega / k$$

$$v_{\vec{k}} = v_{ph}$$

$\rightarrow$

$$\omega = \vec{v} \cdot \vec{k}$$

Stationary outflow of plasma

The two-stream instability may be caused by the following.

1. The ultra-relativistic beam of primary particles (*Ruderman* **&** *Sutherland*, ***ApJ***, **196**, *51*, *1975).*

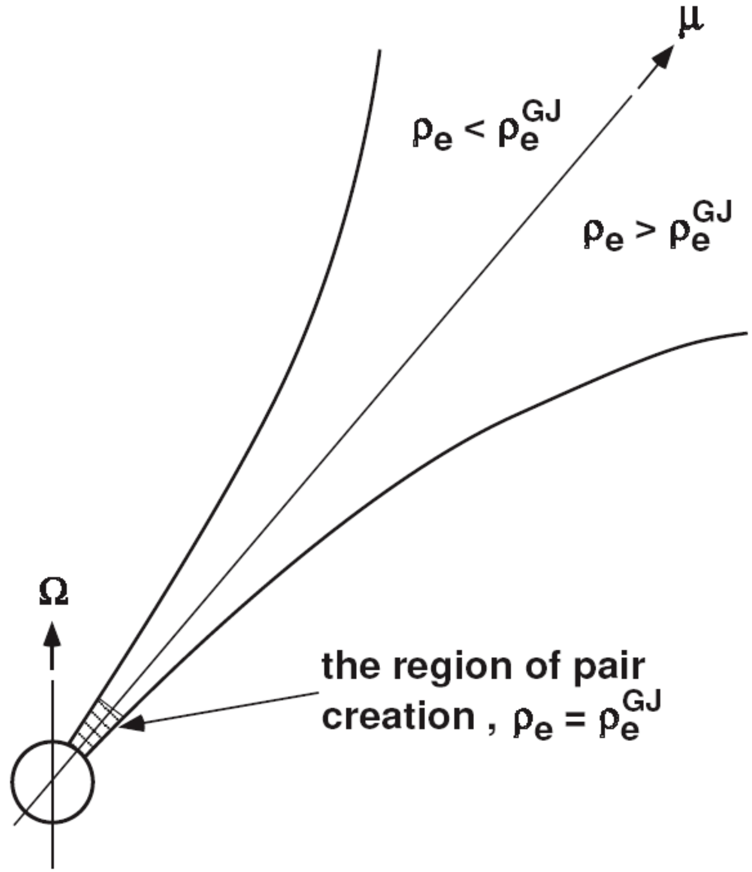
2. The relative motion of electrons and positrons of the secondary pair plasma (*Cheng* **&** *Ruderman*, ***ApJ***, **212**, *800*, *1977).*

The characteristic time for development of the first kind of instability in the pulsar frame is

$$\tau_{RS} \simeq (n_p / n_b)^{1/3} \Gamma_b \Gamma_p^{1/2} \omega_p^{-1} \sim 10^{-4} (r/R)^{3/2} \ s$$

The escape time is $\tau_{esc} \simeq r/c \simeq 3 \times 10^{-5} (r/R) \ s < \tau_{RS}$.

The instability has no enough time to be developed (*Benford* **&** *Buschauer*, ***MNRAS***, **179**, *189*, *1977).*



In a steady-state magnetosphere with $\vec{E}\cdot\vec{B}=0$ the charge density is

$$\rho_e^{GJ} = -\frac{\vec{\Omega}\cdot\vec{B}}{2\pi c}.$$

$$\rho_e \propto B, \quad \rho_e^{GJ} \propto B\cos\chi,$$

where $\chi = \angle \vec{B},\vec{\Omega}$.

The velocity difference between the positrons and the electrons is

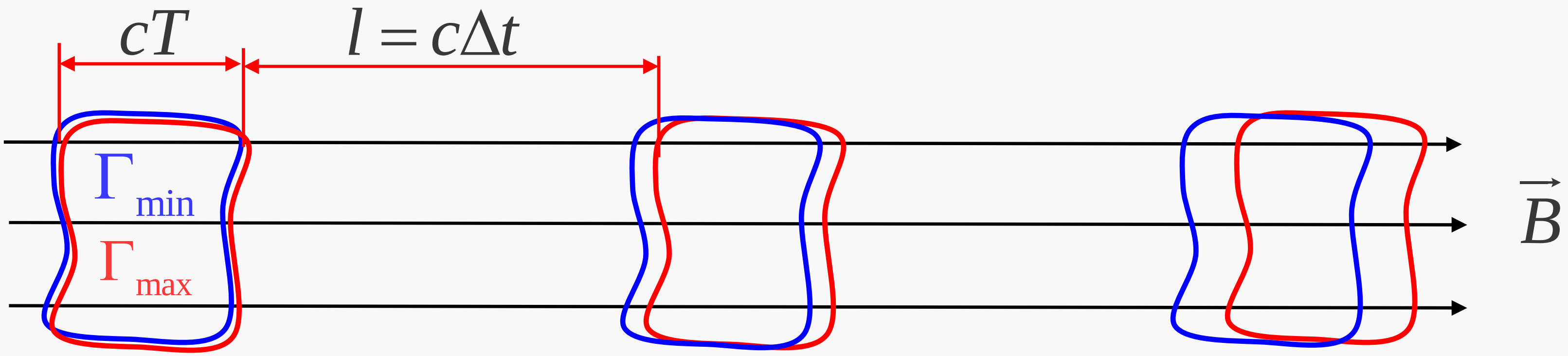
$$\frac{\Delta v}{c} = \frac{v_+ - v_-}{c} \simeq \frac{n_{b_0}}{n_{p_0}}\left(\frac{\vec{\Omega}\cdot\vec{B}}{(\vec{\Omega}\cdot\vec{B})_0} - 1\right).$$

The instability is stabilized by the plasma temperature

(*Buschauer* **&** *Benford*, ***MNRAS***, **179**, *99*, *1977).*

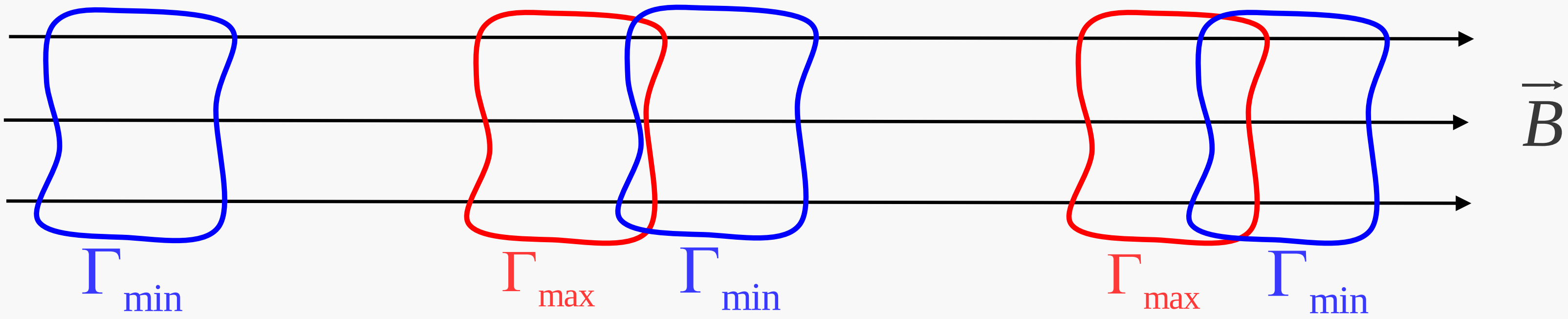
Non-stationary outflow of plasma

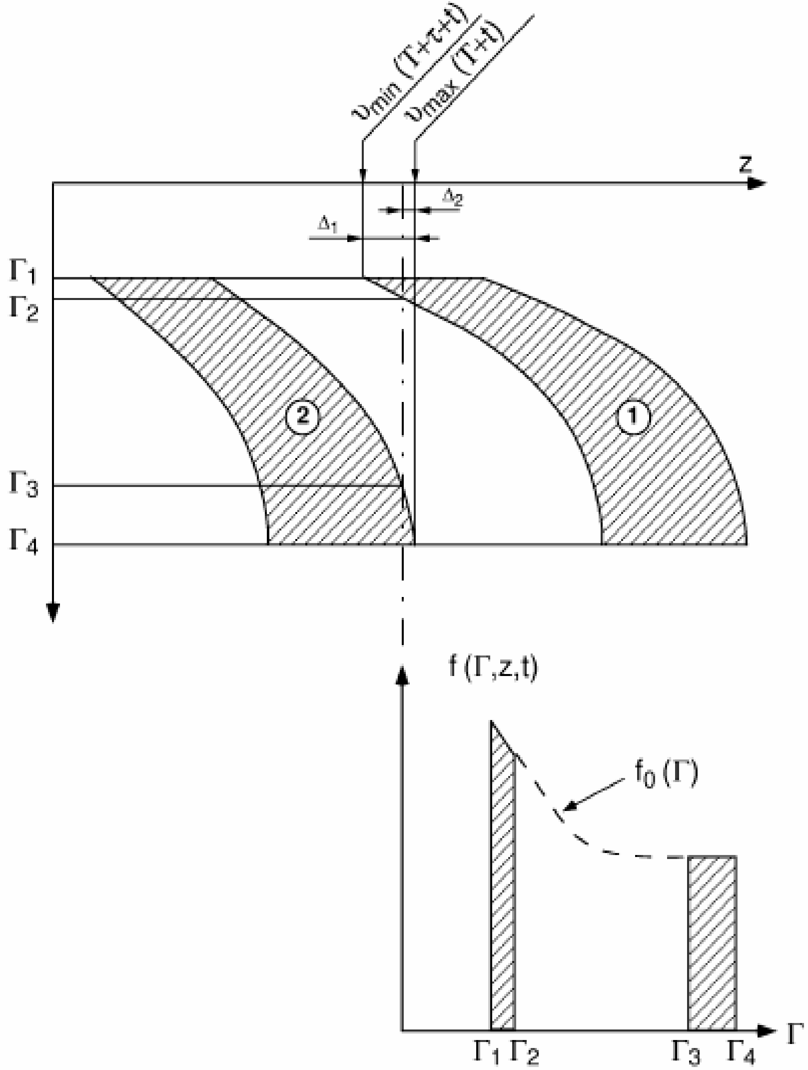
(*Usov*, ***ApJ***, **320**, *333*, *1987*; *Asseo* **&** *Melikidze*, ***MNRAS***, **301**, *59*, *1998*; *Gil* **&** *Mitra*, ***ApJ***, **550**, *383*, *2001*).



$$t \geq t_o = \frac{v_{\rm min}(T + \Delta t) - v_{\rm max} T}{v_{\rm max} - v_{\rm min}} \simeq 2\Gamma^2_{\rm min} \Delta t$$

$$\text{or} \quad r \geq r_{two-str} = c t_o \simeq 2 l \Gamma^2_{\rm min} \simeq 2 \times 10^7 \left(\frac{l}{10^5 cm} \right) \left(\frac{\Gamma_{\rm min}}{10} \right)^2 cm.$$





The dispersion equation for L waves is

$$1-\omega_p^2\int\frac{f(\Gamma,z,t)\ d\Gamma}{\Gamma^3(\omega-kv)^2}=0,\quad \vec{k}\parallel\vec{v}\parallel\vec{B}.$$

$$\Downarrow$$

$$1-\omega_p^2\left[\frac{\alpha}{(\omega-kv_2)^2}+\frac{\beta}{(\omega-kv_4)^2}\right]=0,$$

where $\alpha=\int_{\Gamma_1}^{\Gamma_2}\frac{f_0(\Gamma)}{\Gamma^3}d\Gamma,\ \beta=\int_{\Gamma_3}^{\Gamma_4}\frac{f_0(\Gamma)}{\Gamma^3}d\Gamma.$

The maximum growth rate is

$$\mathrm{Im}\ \omega_{max}=\frac{\sqrt{3}}{2}\alpha^{1/2}\left(\frac{\beta}{2\alpha}\right)^{1/3}\omega_p$$

and occurs for $k_{res}=\frac{\alpha^{1/2}\omega_p}{v_4-v_2}.$

The development of the two-stream instability already occurs when the cloud overlap is small $(\sim 10^4\,cm)$.

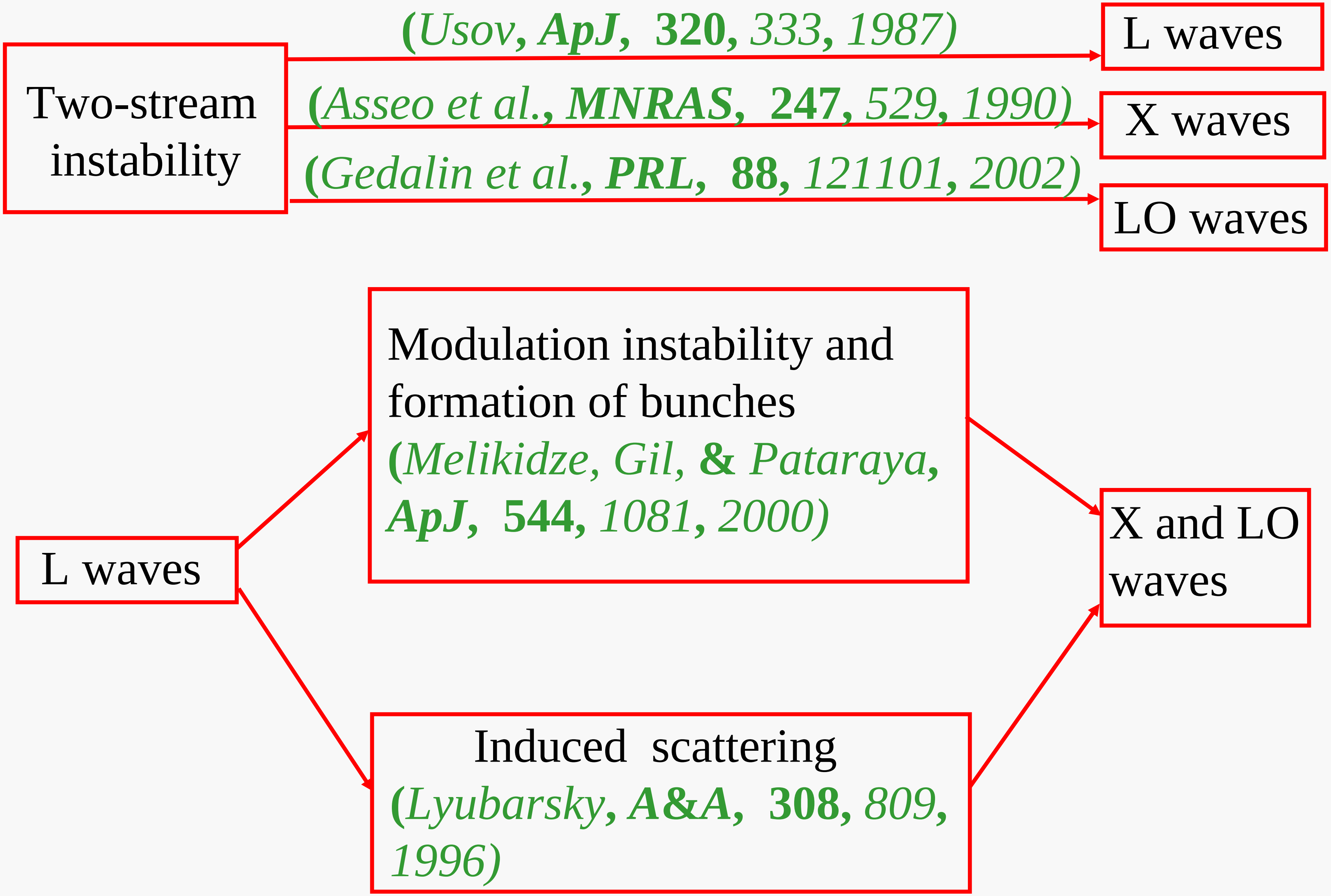
This problem studied numerically by *Saito & Sakai* (***ApJ*, 602,** *L41, 2004).*

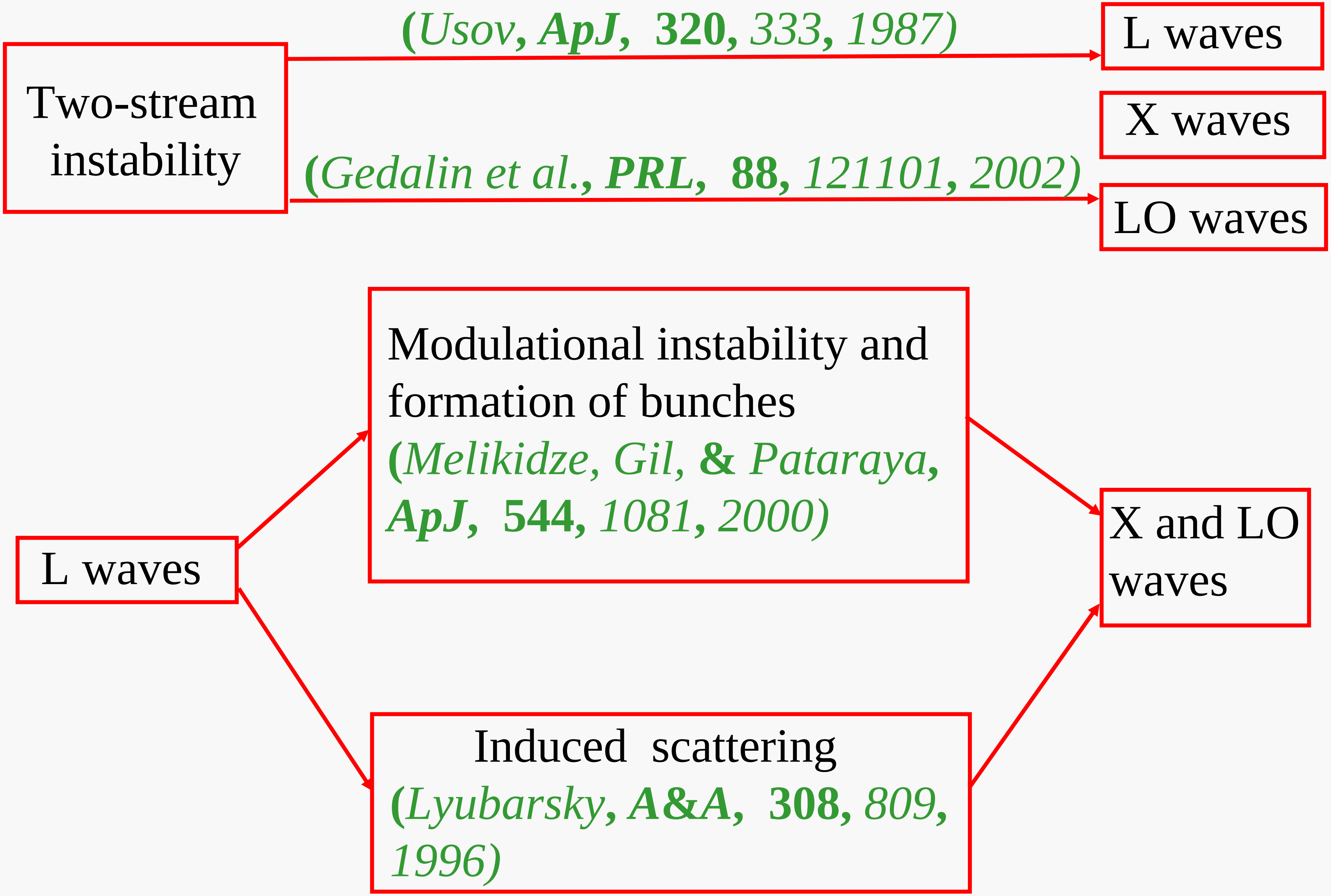
Some conclusions

The two-stream instability may be developed in the inner magnetosphere, i.e., at the distance of $r_{t-s} \simeq 2l\Gamma^2_{\min} \simeq 10^7 - 10^8\ cm.$

The existence of several scales of the out-flowing plasma modulation may lead to several regions of radio emission.

This is consistent with observations **(***Gil***, *ApJ*, 299,** *154***,** *1985;* *Kijak* **&** *Gil* *,* ***MNRAS*, 299,** *855***,** *1998).*


Two-stream instability
(*Usov*, ***ApJ*****, 320,** *333*, *1987)*
L waves
(*Asseo et al.*, ***MNRAS*****, 247,** *529*, *1990)*
X waves
(*Gedalin et al.*, ***PRL*****, 88,** *121101*, *2002)*
LO waves
L waves
Modulation instability and formation of bunches
(*Melikidze*, *Gil*, **&** *Pataraya*, ***ApJ*****, 544,** *1081*, *2000)*
Induced scattering
(*Lyubarsky*, ***A&A*****, 308,** *809*, *1996)*
X and LO waves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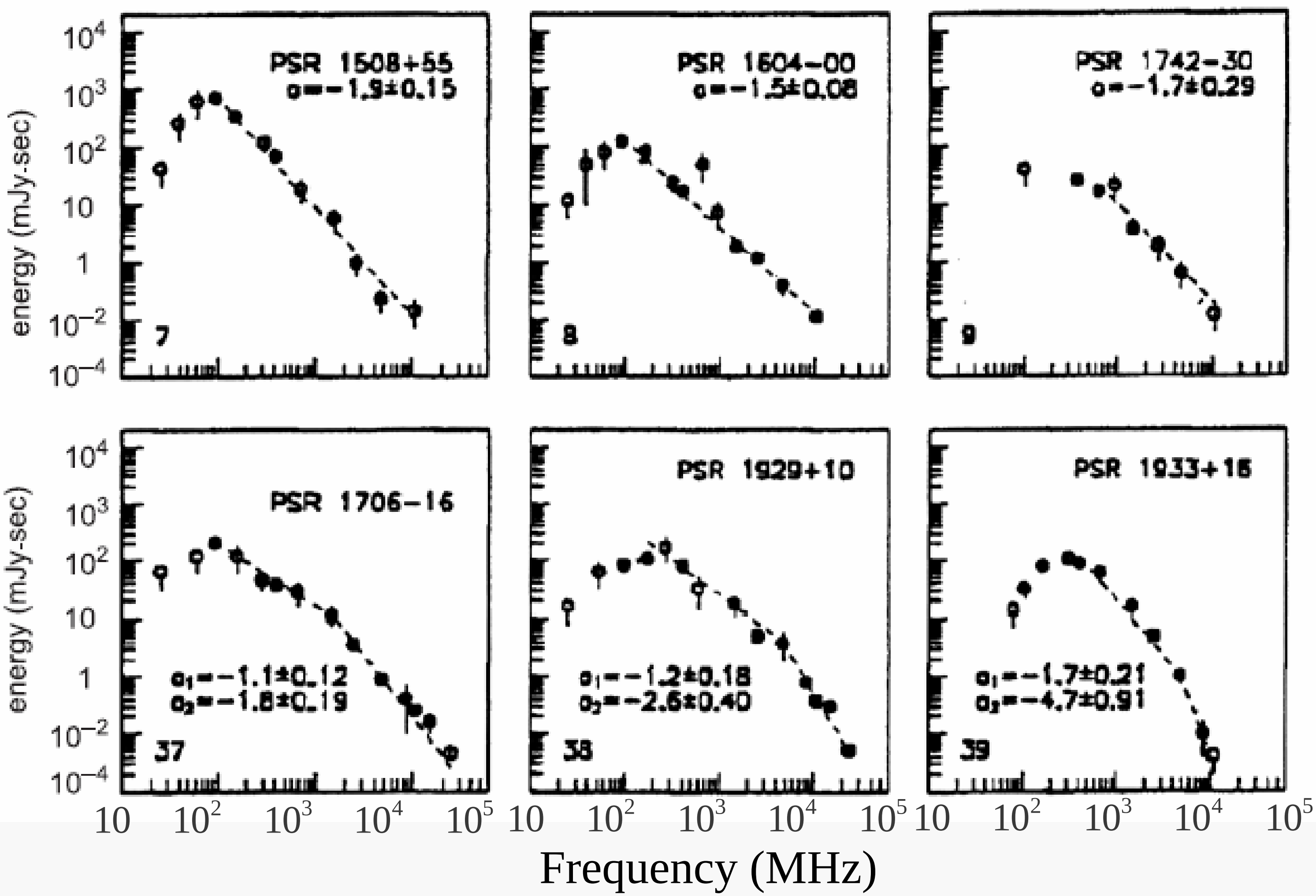
(*Gedalin, Gruman,* **&** *Melrose*, ***PRL*****, 88,** *121101***,** *2002)*

- Additional solutions (called beam modes) of the dispersion relation for the beam-plasma system are found, and it is shown that these modes can be amplified.

- In the process of propagation the beam waves evolve into O mode when their frequency matches the resonant frequency.

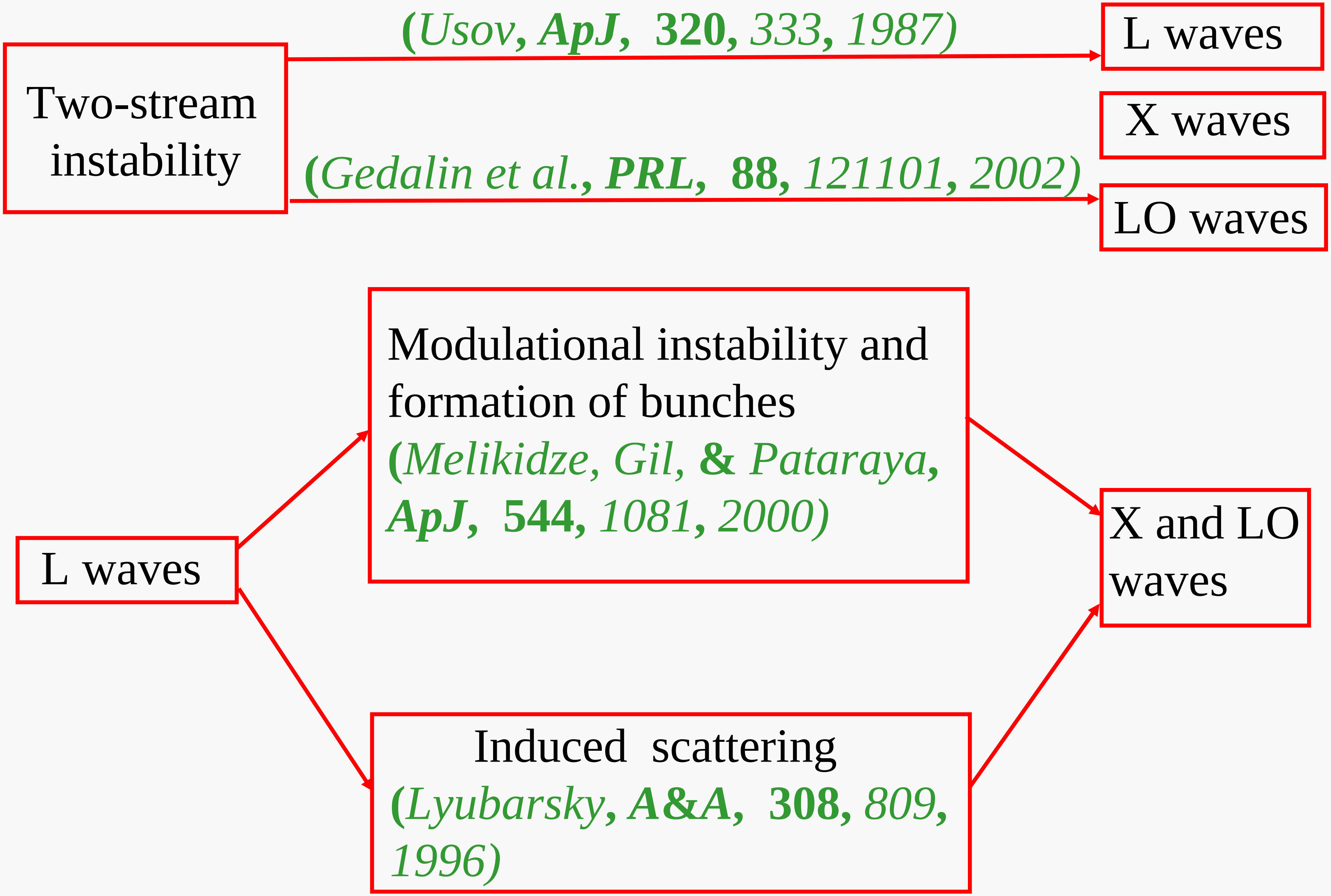
- The spectrum of the escaping radiation has a maximum at the frequency $\omega_{max} \sim 0.1\omega_{p_0}\Gamma_p^{1/2}$. The efficiency of wave growth decreases at both $\omega < \omega_{max}$ and $\omega > \omega_{max}$.
  The implied form of spectrum is consistent with observations.

Radio spectra of PSRs



$\bar{\alpha} \simeq 1.7$

(*Siber*, ***A&A*, 28,** *237, 1973; Backer* **&** *Fisher*, ***ApJ*, 189,** *137, 1974; Lyne* **&** *Manchester*, ***MNRAS*, 234,** *477, 1988; Malofeev et al.*, ***A&A*, 285,** *201, 1994; Lorimer et al.*, ***MNRAS*, 273,** *411, 1995)*


Two-stream instability
(*Usov*, ***ApJ*****, 320,** *333*, *1987)*
L waves
X waves
(*Gedalin et al.*, ***PRL*****, 88,** *121101*, *2002)*
LO waves
L waves
Modulational instability and formation of bunches
(*Melikidze*, *Gil*, **&** *Pataraya*, ***ApJ*****, 544,** *1081*, *2000)*
Induced scattering
(*Lyubarsky*, ***A&A*****, 308,** *809*, *1996)*
X and LO waves

Formation of bunches

- Two-stream instability = bunching instability (*Ruderman* **&** *Sutherland*, ***ApJ*****, 196,** *51*, *1975).*

Formation of bunches

- Two-stream instability $\neq$ bunching instability **(***Ruderman* **&** *Sutherland***, *ApJ*, 196,** *51***,** *1975).*

- Bunches formed by linear electrostatic waves cannot provide any emission **(***Melikidze, Gil,* **&** *Pataraya***, *ApJ*, 544,** *1081***,** *2000).*

- The modulational instability in the turbulent plasma may generate charged solitons only if species of different charge have different masses **(***Karpman et al.***, *Phys. Scr.*, 11,** *271***,** *1975).*

- To explain coherent radio emission of PSRs it is not necessary stable solitons but only large-scale (as compared with Langmuir wavelength) charge density fluctuations **(***Gil, Lyubarsky* **&** *Melikidze***, *ApJ*, 600,** *872***,** *2004).*

Radiation of bunches

$$\nu_c \simeq \frac{3c}{4\pi\rho}\Gamma^3 \simeq 10^2 \left(\frac{\Gamma}{10^2}\right)^3 \left(\frac{\rho}{10^8 cm}\right)^{-1} \text{ MHz} .$$

$$\boxed{\Gamma_p \geq 10^2}$$

The total energy emitted may be as high as $I_c \simeq N^2 I_{sp}$, where N is the number of charged particles cooperating in the radiation and I_{sp}, is the energy emitted by a single particle. (*Ginzburg* **&** *Zheleznyakov*, ***Ann. Rev. A&A***, **13**, *511*, *1975*)

For a typical PSR, at $r \sim 10^7 cm$ the plasma density is $n_p \sim 10^{10} cm^{-3}$. For radio emission at $\nu \sim 10^3$ MHz we have $N < N_{\max} \sim n_p \lambda^3 \sim 10^{14}$, where $\lambda = c/\nu = 30\ cm$.

The brightness temperature: $T_b \leq \Gamma mc^2 / k \sim 10^{25} (\Gamma / 10^2)$ K.

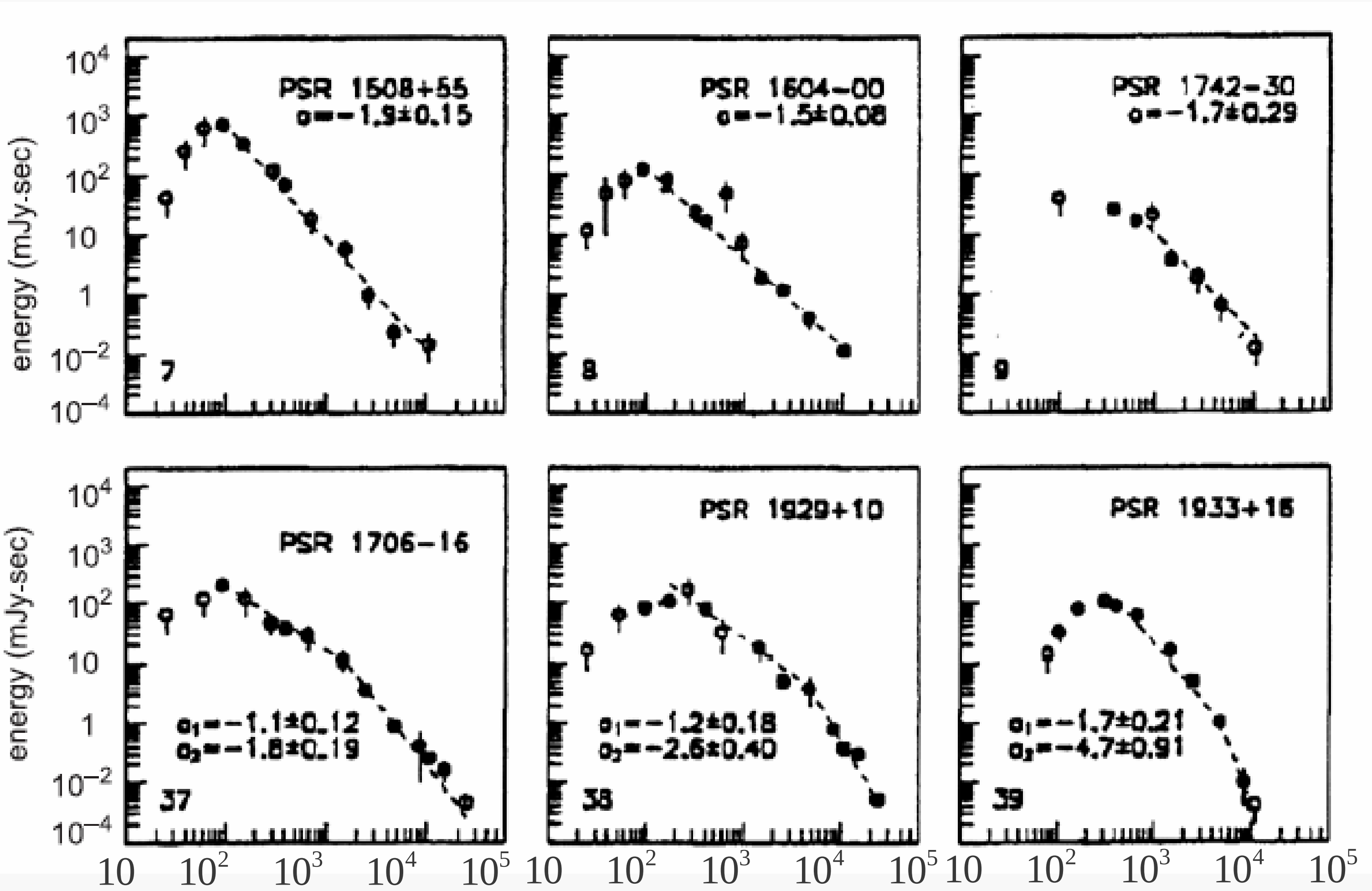
- Curvature radiation (CR) of single bunches (influence of dimensions) in vacuum (*Saggion*, ***A&A*****, 44,** *285*, *1975; Benford* **&** *Buschauer* , ***MNRAS*****, 177,** *109*, *1976;* ***A&A*****, 118,** *358*, *1983).*

- CR of single bunches in a pulsar plasma (*Gil*, *Lyubarsky* **&** *Melikidze*, ***ApJ*****, 600,** *872*, *2004).*
  1. **The polarization of CR emitted in plasma is that of X mode.**
  2. $\omega < 2\Gamma_p^{1/2}\omega_p \sim 20\ (\Gamma_p/10^2)^{1/2}$ GHz .
  3. **CR is largely suppressed compared with the vacuum case, but high enough to explain the observed PSR luminosities.**

- CR of systems of bunches with monoenergetic and power-law spectra, taking into account self-absorption *(Ochelkov* **&** *Usov*, ***Ap&SS*****, 69,** *439*, *1980;* ***Nature***, ***309***, *332*, *1984).*

  The radio spectra of PSRs may be explained by CR of bunches.

Radio spectra of PSRs



$\bar{\alpha} \simeq 1.7$

(*Siber*, ***A&A*, 28,** *237, 1973; Backer* **&** *Fisher*, ***ApJ*, 189,** *137, 1974; Lyne* **&** *Manchester*, ***MNRAS*, 234,** *477, 1988; Malofeev et al.*, ***A&A*, 285,** *201, 1994; Lorimer et al.*, ***MNRAS*, 273,** *411, 1995)*

Some properties of normal modes

- X mode with $\vec{e} \parallel \vec{k} \times \vec{B}$ cannot effectively interact with particles moving strictly along $\vec{B}$ through Cherenkov resonance.

- X mode waves may be produces either through cyclotron instability or some nonlinear processes.

- X mode is not Landau damped, and it can be damped through cyclotron resonance.

- LO mode can interact with particles through Cherenkov resonance provided that the parallel phase velocity is less than c.

- The subluminous O mode cannot escape the pulsar magnetosphere because of Landau damping while the superluminous O mode can do this.

Cyclotron instability in pulsar magnetospheres

(*Machabeli* **&** *Usov*, ***Sov. Astron. Lett*****, 5,** *238***,** *1979; Lyutikov, Blandford, and Machabeli*, ***MNRAS*****, 305,** *338, 1999)*

The observed radio emission of PSRs may be produced directly by a maser-type plasma instability operating at the anomalous cyclotron-Cherenkov resonance $\omega - k_{\parallel} v_{\parallel} + \omega_B / \Gamma_{res} = 0.$

Cyclotron instability develops if $\left(\dfrac{\omega_p}{\omega_B}\right)^2 \geq \dfrac{\Gamma_p^2}{\Gamma_t}.$ $\quad \left(\dfrac{\omega_p}{\omega_B}\right)^2 \propto r^3.$

$$\Downarrow$$

$$r_c \simeq R \left(\frac{\Gamma_p^2}{\Gamma_t}\right)^{1/3} \left(\frac{\omega_{B_0}}{\omega_{p_0}}\right)^{2/3},$$

$r_c \simeq 10^9 - 10^{10}\, cm \simeq (0.1-1)\dfrac{c}{\Omega}$ for $\Gamma_p \simeq 5$ and $\Gamma_t \simeq 10^4 - 10^6.$

$$\boxed{\Gamma_p \leq 10}$$

Some observational consequences of the cyclotron model of PSRs

- The cyclotron instability can develop only near the light cylinder.
- The frequency dependence of the radio pulse width is $\Delta\varphi(\nu) \propto \nu^{-1/7}$.
- The predicted spectral index is $\alpha = 2,\ F(\nu) \propto \nu^{-\alpha}$.
- The tail (or beam) particles undergo transitions to the states with *higher* transverse momentum and emit photons via synchrotron mechanism, i.e., the region of cyclotron instability is a source of high-frequency (optic, X-ray and gamma-ray) emission (*Machabeli* **&** *Usov*, ***Sov. Astron. Lett*, 5,** *238***,** *1979;Lominadze et al.*, ***Ap&SS*, 90,** *19, 1983; Malov* **&** *Machabeli*, ***ApJ***, **554**, *578, 2001)*

Some properties of normal modes

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- The subluminous O mode cannot escape the pulsar magnetosphere because of Landau damping while the superluminous O mode can do this.

Cherenkov drift instability in pulsar magnetospheres

(*Kazbegi, Machabeli* **&** *Melikidze*, ***MNRAS*, 253,** *377*, *1991;*
Lyutikov, Blandford, and Machabeli, ***MNRAS*, 305,** *338, 1999;*
Shapakidze et al., ***Phys*. *Rev*. *E*, 67,** *026407, 2003)*

The Cherenkov drift instability may occur at the resonance

$$\omega(k) - k_{\|} v_{\|} - k_{\perp} u_d = 0 \ ,$$

where $u_d = \Gamma v_{\|} c / (\omega_B \rho)$ is the drift velocity.

$$r_{C-d} \simeq (0.1-1)\frac{c}{\Omega} \ \ for \ \ \Gamma_p \simeq 5 \ \ and \ \ \Gamma_b \simeq 10^6 - 10^7.$$

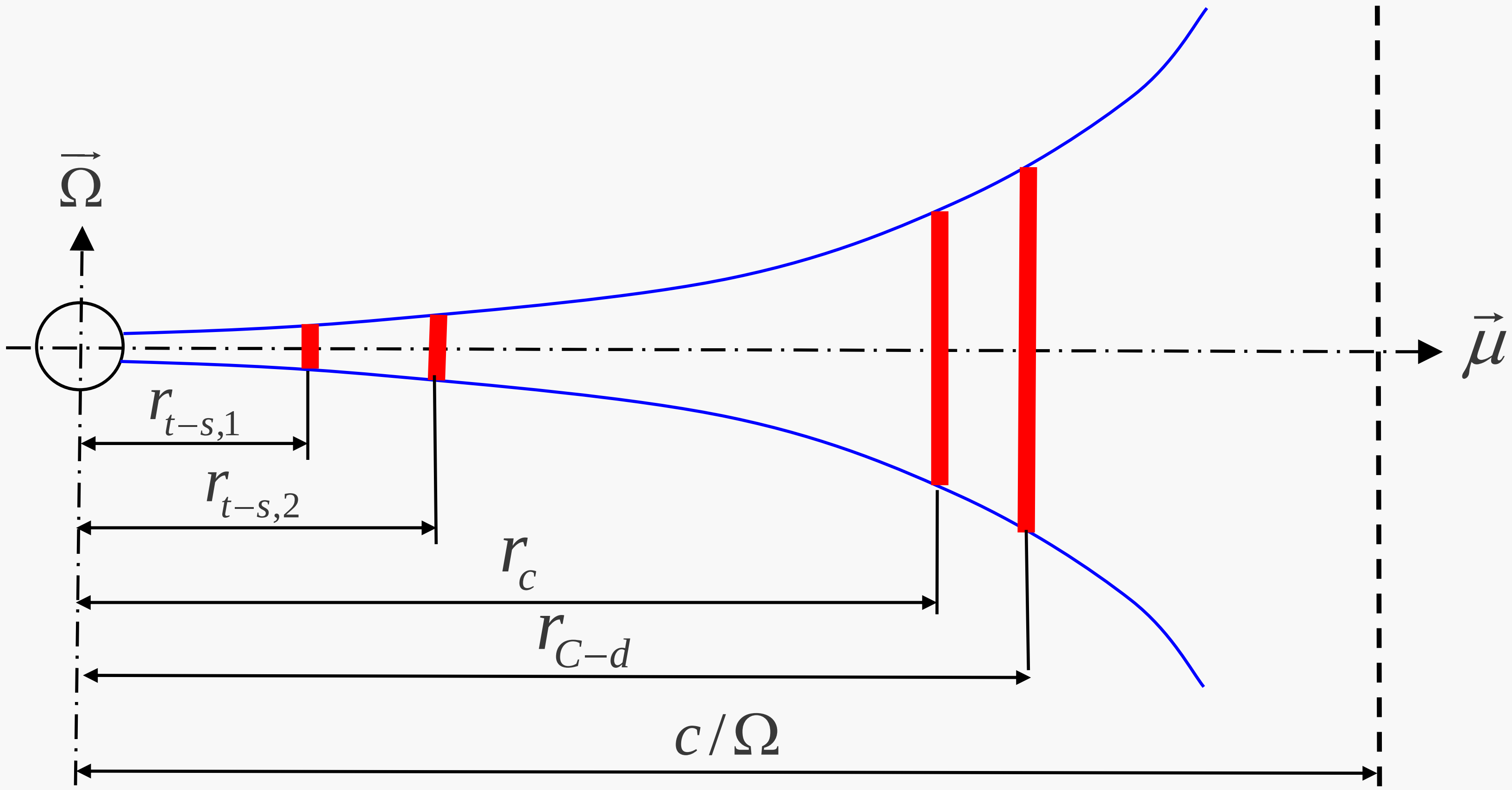
$$\boxed{\Gamma_p \leq 10}$$

The Cherenkov drift instability does not have a simple dependence of the emission altitude on the frequency because the resonant condition for this instability are virtually independent of frequency.

Conclusions

- The pulsar plasma is an active medium that can amplify its normal modes.

- There are a few instabilities that may occur in pulsar magnetospheres.



- The cyclotron and Cherenkov drift instabilities may be developed in a low-energy pulsar plasma, $\Gamma_p \leq 10$.

- If the radio emission regions of PSRs are far inside the light cylinder, $r_{rad} \ll c/\Omega$, the two-stream instability is a plausible reason of the radio emission generation, while if they are near the light cylinder, $r_{rad} \sim c/\Omega$, most probably, the radio emission of PSRs is generated directly via the cyclotron and Cherenkov drift instabilities.

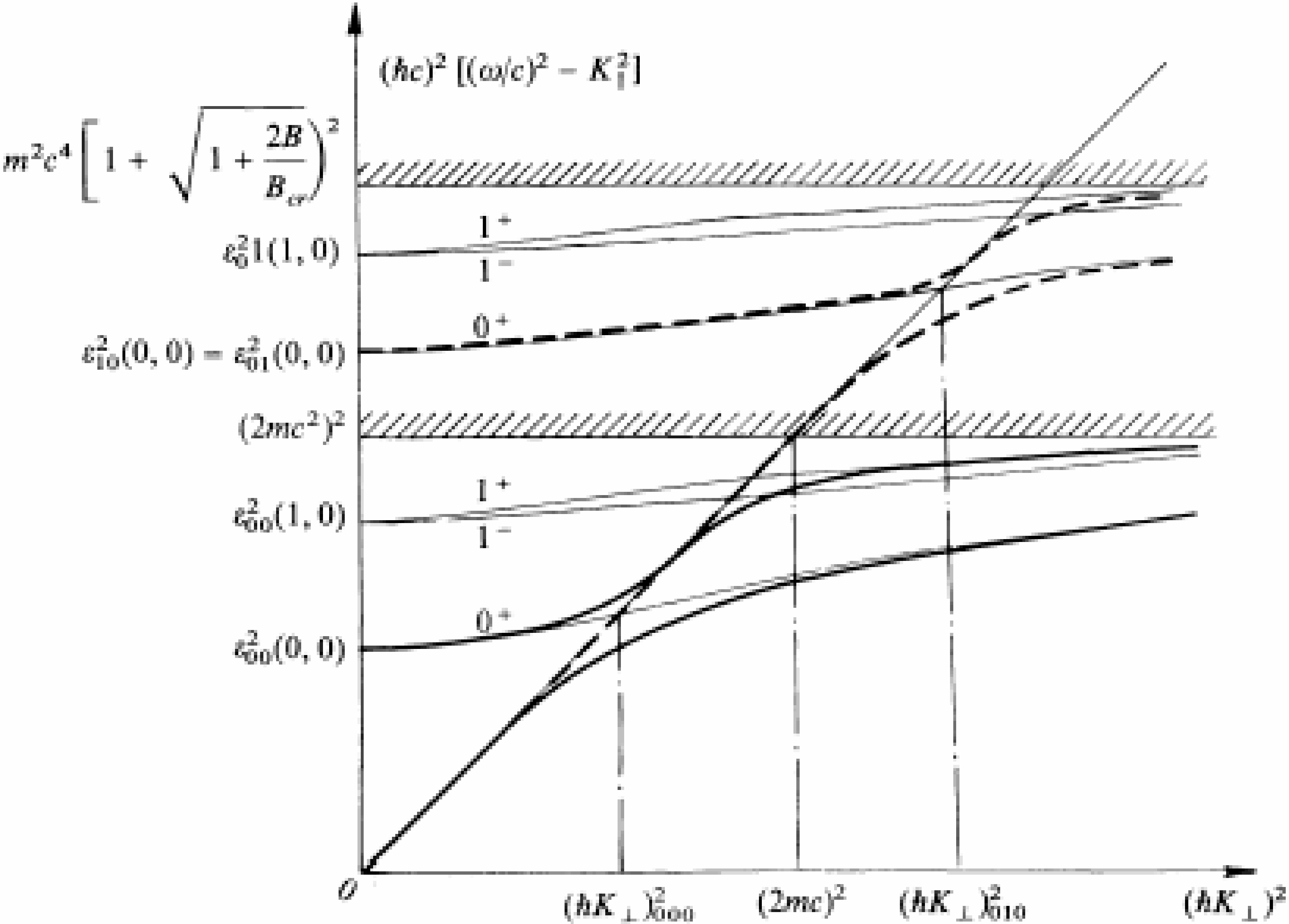


Figure 9. Dispersion curves for photons propagating in a strong magnetic field. The sloped straight line is the unperturbed dispersion curve $(\omega/c)^2 - K_\parallel^2 = K_\perp^2$.

Refraction of radio waves in the ultra-relativistic highly magnetized pulsar plasma is frequency-dependent and can lead can modify the spectra of PSRs **(***Petrova***, *A&A*, 383,** *1067***,** *2002).*

Refraction of radio waves can change the radio pulses **(***Petrova***, *A&A*, 360,** *592***,** *2000).*

Arons & Barnard (1986) have derived the dispersion relation for three wave modes which can propagate through the plasma of a pulsar magnetosphere: the ordinary subluminous mode (subluminous O-mode), the ordinary superluminous mode (superluminous O-mode) and the extraordinary mode (X-mode). The X-mode does not suffer refraction, but refraction of the subluminous O-mode can be considerable in pulsar magnetospheres (Barnard & Arons 1986). The subluminous O-mode cannot escape the pulsar magnetosphere due to Landau damping, so it does not contribute directly to the observed emission. Lyubarskii (1996) has shown that the subluminous O-mode can be converted into the superluminous O-mode – which can escape the magnetosphere – by induced scattering off plasma particles. As pointed out by Barnard & Arons (1986) refraction of the superluminous O-mode is less severe than for the subluminous O-mode. It can, however, be important in the presence of a transverse plasma density gradient.

Let us consider propagation of a superluminous wave. In a steady state medium with smooth density gradients, the wave frequency remains constant while the wavelength is adjusted in order to satisfy the dispersion equation at any point. In the (ω, k) plane, the point representing a wave moves along the dispersion curve upward because plasma frequency decreases together with plasma density. If the wave propagates strictly along the magnetic field, it transits along the dispersion curve to the subluminous region. Eventually the wave phase velocity, ω/k, decreases such that the wave decays through the Landau damping. In the oblique propagation case, the wave remains superluminous and at $\omega \gg \omega_0$ transforms into the vacuum transverse electromagnetic wave, which escapes freely [1]. Finally it should be noted that in a curved magnetic field, a wave becomes oblique, even if it was initially directed along the magnetic field (Barnard & Arons 1986, Lyubarskii & Petrova 1998). Therefore the superluminous longitudinal waves eventually escape from pulsar magnetospheres in the form of the vacuum transverse electromagnetic waves.

Applying the same consideration to the subluminous waves, one can see that such waves do not escape. When they propagate in the plasma of decreasing density, their phase velocities decrease and eventually the waves decay through the Landau damping. So in the strong magnetic field the superluminous wave escapes even if it was initially purely longitudinal (in the curved magnetic field) whereas the subluminous waves does not escape even though these waves are nearly transverse at $\omega \ll \omega_0$.

The two-stream instability generates predominantly longitudinal waves, which are in Cherenkov resonance with the particle beam, $\omega = kv$. This waves are evidently subluminous, $\omega/k < c$ (the region where the waves are generated is shaded in Figs. 1, 2). Such waves are unable to escape from plasma unless nonlinear processes redistribute the wave energy into the superluminous region. High brightness temperature of pulsar radio emission implies high wave energy density in pulsar magnetospheres and therefore nonlinear effects should be of paramount importance.

The Cherenkov drift instability, on the other hand, does not have a simple dependence of the emission altitudes on the frequency. The resonance conditions for the Cherenkov drift instability are virtually independent of frequency (equation C1), so the location of the emission region is determined by the various conditions on the development of the instability (Appendix C).

It is more natural to consider Cherenkov drift emission in a curved magnetic field as an analogue of the Cherenkov emission with the drift of the resonance particles taken into account, than as a type of curvature emission. From the microphysical point of view the emission is again the result of the polarization shock front that develops owing to the passage of a superluminal particle through a medium, so it is required that the emitting particle propagates with a velocity greater than the phase velocity of the emitted waves. The Cherenkov drift maser is impossible in vacuum, unlike the curvature emission, which is a close analogue of the conventional cyclotron emission and is possible in vacuum. The curvature provides only the drift component of the velocity, which is essential for the coupling of the resonant particle to the emitted electromagnetic wave.

Cherenkov drift instability produces waves with the linear polarization perpendicular to the plane of the curved field line. This is in sharp contrast to many other theories of the radio emission that tend to generate waves with the electric field in the plane of the curved field line. If one can determine the absolute position of the rotational

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A non-linear radio pulsar emission mechanism

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SUMMARY

We examine a coherent pulsar emission mechanism based on the presumption that such a process results from the development of the relativistic two-stream instability in the magnetosphere of the neutron star. We specify linear and non-linear stages of the development of this instability for the physical situation described in the Cheng & Ruderman model. The electron–positron magnetospheric plasma pervaded by the beam of relativistic primary particles is immersed in a superstrong but finite magnetic field. The linear treatment shows the relevance of a dispersion relation specific to pulsars and the importance of the resulting unstable Langmuir wave (i.e. plasma wave) solution, with simultaneous electrostatic and electromagnetic characteristic features. Nevertheless, the electromagnetic flux derived from the linear study is insufficient to account for the high level of observed pulsar radio emission. The non-linear treatment describes the evolution of the two-stream interaction and shows the stability of Langmuir soliton-like solutions in the magnetospheric pulsar plasma. We propose to call these solutions Langmuir microstructures and infer the existence of a lattice of such microstructures in the pulsar magnetosphere. These Langmuir microstructures naturally give rise to two different types of radiation mechanisms. The first is a direct radiation by the microstructures themselves, when they are perturbed in a direction perpendicular to the magnetic field lines. We show that the available radiation and the spatial extent of the Langmuir microstructures, as derived from the non-linear study, can account for both observed radio luminosities and temporal microstructures. The second radiation mechanism, due to the beam or plasma particles streaming through the lattice of Langmuir microstructures, appears insufficient to produce a radiated power of the order of those observed. Our results emphasize, for the first time, the importance for pulsar radio emission of the direct radiation process from perturbed Langmuir microstructures.

is fully electromagnetic. It has also been shown recently by Asséo et al. (1980) that a two-stream electrostatic instability can produce a vacuum electromagnetic radiation if the beams have finite transverse

dimensions. In this paper the mathematics was limited to a thick beam for which the finite field line curvature does not modify the dispersion relation.

The second information is the possibility of convectively amplified wave packets along the field lines: the growth is not modified if the wave packet has an extension $\Delta\ell \gtrsim r_o\ m^{-1/3}$, which is sufficient to include inhomogeneities along the field lines. The Poynting flux along the outside B field is larger than across the field by a large factor $m^{1/3}$.

In the opposite limit, for a standard two-stream situation and thickness larger than a few meters (with standard parameters) the radiation term is negligible in the dispersion relation and one recovers the results of Asséo et al. (1980). As far as the total radiated power is concerned it is possible to obtain the experimental figures only if the beams are cold enough, energetic ($\gamma \sim 10^3$, 10^4) and the density fluctuations of order 10^{-1} (the beam density being related to the observed frequency by the dispersion relation). The observed frequency spectrum may be related to the variation of the plasma frequency of the dominant beam due to the divergence of the magnetic field lines (Pellat 1979).

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Asséo, E., Pellat, R., and Rosado, M.: 1980, Astrophys. J. 239, p. 661.
Goldreich, P. and Keeley, D.A.: 1971, Astrophys. J. 170, p. 463.
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Pellat, R.: 1979, Space Sci. Rev. 24, p. 601.

time, despite each mode having its own properties. A number of authors argued for the identification of OPMs as the natural polarization modes in the pulsar magnetosphere (e.g. Barnard & Arons 1986; McKinnon 1997; von Hoensbroech et al. 1998; Petrova 2001). Elliptically polarized natural modes could then provide the origin for the circular polarization as a propagation effect.

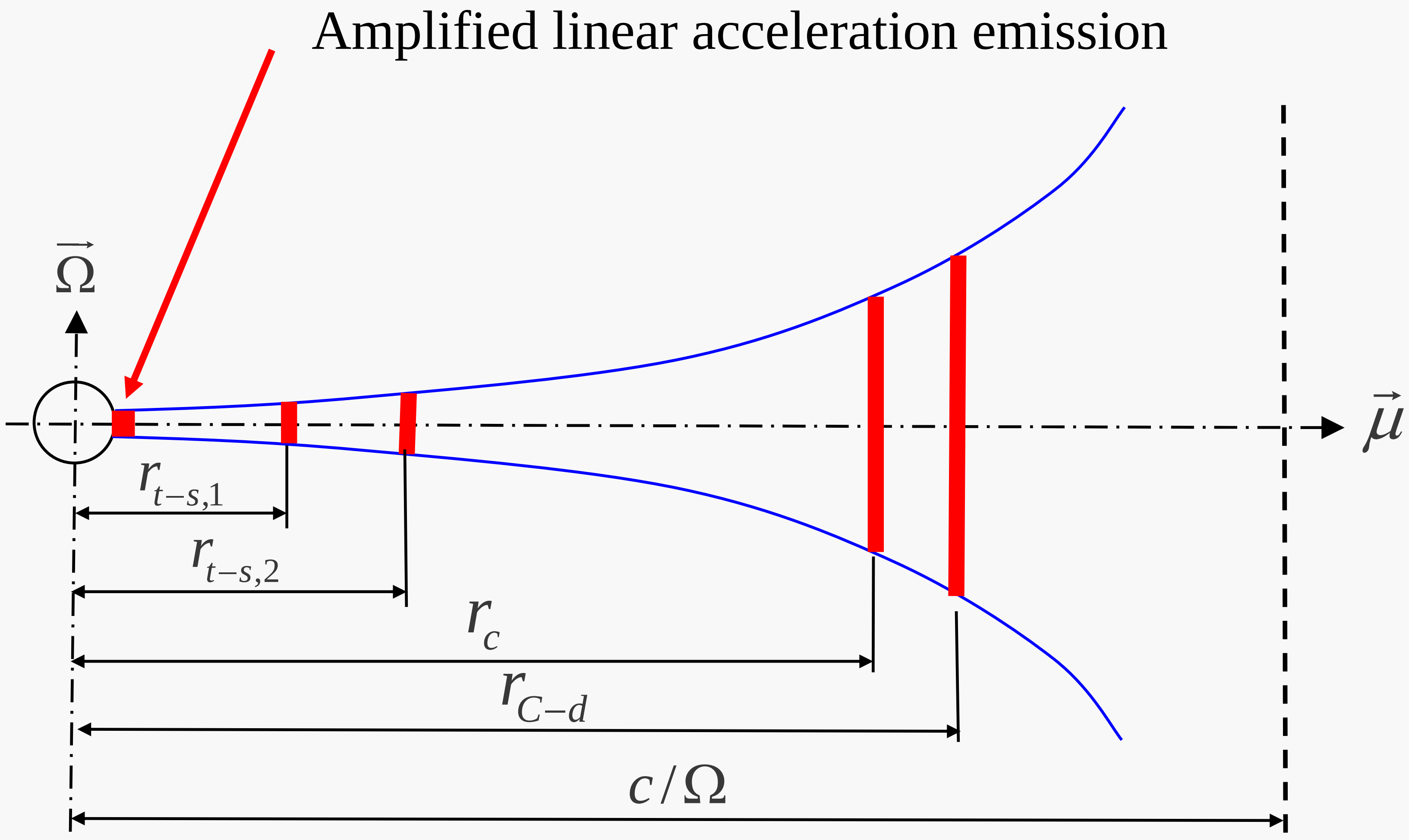
J. A. Gil[1], G. I. Melikidze[1,2], and D. Mitra[3] A&A 388, 235–245 (2002)

Cooke 1969). However the structure of the magnetic field at the surface of the neutron star is largely unknown. Strong non–dipolar surface magnetic fields have long been thought to play an important role in the radio emission of pulsars. For example, in order to sustain pair production in vacuum gaps, the Ruderman & Sutherland (RS75) model implicitly assumed that the radius of curvature of field lines above the polar cap should be about 10^6 cm, of non–dipolar components. It is believed that thermal X-rays from pulsars are a good diagnostic tool to infer the structure of the surface magnetic field. Soft X-ray observations of pulsars show non-uniform surface temperatures which can be attributed to small scale magnetic anomalies on the pulsar polar cap (e.g. Page & Sarmiento 1990; Bulik et al. 1992, 1995). Several similar arguments in favour of the non-dipolar nature of the surface magnetic field can also be found in Becker & Trümper (1997); Cheng et al. (1998); Rudak & Dyks (1999); Cheng & Zhang (1999); Thompson & Duncan (1995, 1996), Murakami et al. (1999), and Tauris & Konar (2001). Also several theoretical studies concerning the formation and evolution of non–dipolar magnetic fields in neutron stars are found in the literature (e.g. Blandford et al. 1983; Krolik 1991; Ruderman 1991; Arons 1993; Chen & Ruderman 1993; Geppert & Urpin 1994; Mitra et al. 1999).

3.2. Circular polarization

The radiation from many pulsars contains detectable circular polarization, although the amounts are generally much less than the degree of linear polarization (e.g., Radhakrishnan & Rankin 1990; Han et al. 1998). The circular polarization naturally arises at high altitudes where the cyclotron frequency is already not too large as compared with the radiation frequency. The normal waves are elliptically polarized in this region if the distribution functions of electrons and positrons are different. This is always the case because the Goldraich-Julian charge density should be maintained in pulsar magnetospheres. Therefore the circular polarization in the outgoing radiation may be attributed to the dispersive properties of the magnetospheric plasma provided the polarization-limiting radius is about the light cylinder radius (Melrose & Stoneham 1977; Cheng & Ruderman 1979; Melrose 1979; von Hoensbroech et al. 1998; von Hoensbroech & Lesch 1999; Gedalin et al. 2001).

(*Melrose*, **ApJ**, **225,** *557*, *1978; Rowe.*, **Austr. J. Phys**, **45,** *1*, *1992*)



grows in the laboratory frame. One should also note that the so called amplified linear acceleration emission (Melrose 1978; Rowe 1995) actually represents the induced scattering of a longitudinal, electrostatic wave into a (quasi) transverse one.