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Coherent Mechanisms of Pulsar Radio Emission

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Abstract.

Relativistic plasma masers operating on the anomalous cyclotron-Cherenkov resonance $\omega - k_{||}v_{||} + \omega_B/\gamma_{res} = 0$ and the Cherenkov-drift resonance $\omega - k_{||}v_{||} - k_x u_d = 0$, are capable of explaining the main observational characteristics of pulsar radio emission. Both electromagnetic instabilities are due to the interaction of the fast particles from the primary beam and from the tail of the secondary pairs distribution with the normal modes of a strongly magnetized one-dimensional electron-positron plasma. In a typical pulsar both resonances occur in the outer parts of magnetosphere at $r_{res} \approx 10^9$cm.

1. Emission mechanisms

We have shown (Lyutikov, Blandford & Machabeli 1999b) that pulsar radiation may be generated by two kinds of *electromagnetic* plasma instabilities – cyclotron-Cherenkov instability, developing at the anomalous Doppler resonance

$$\omega(\mathbf{k}) - k_{||}V_{||} + \omega_B/\gamma_{res} = 0 \tag{1}$$

and Cherenkov-drift instability, developing at the Cherenkov-drift resonance

$$\omega(\mathbf{k}) - k_{||}V_{||} - k_x u_d = 0 \tag{2}$$

The cyclotron-Cherenkov instability is responsible for the generation of the core-type emission and the Cherenkov-drift instability is responsible for the generation of the cone-type emission. These *electromagnetic* instabilities are the strongest instabilities in the pulsar magnetosphere (Lyutikov 1999a).

Both instabilities are maser-type in a sense that an induced emission dominates over spontaneous. From a classical viewpoint, a random incoming wave forces a particle to emit a wave "in phase" with initial one, so that the resulting intensity is proportional to N^2 where N is a number of the interfering waves.

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This is how coherence of the radiation is produced: masers naturally produce coherent waves. For the operation of a maser some kind of population inversion condition should be satisfied: there should be more emitting that absorbing particles.

The cyclotron instability can develop on both primary beam and on the tail of the plasma distribution while the Cherenkov-drift instability develops on the rising part of the primary beam distribution function. The free energy for the growth of the instability comes from the nonequilibrium anisotropic distribution of fast particles.

From the microphysical point of view both emission process habe more similarities with Cherenkov-type emission than with synchrotron or curvature emission. In the case of Cherenkov-type process the emission may be attributed to the electromagnetic polarization shock front that develops in a dielectric medium due to the passage of a charged particle with speed larger than phase speed of waves in a medium. It is a collective emission process in which all particles of plasma take part.

Interestingly, in a cyclotron-Cherenkov emission process an emitting particle undergoes a transition *up* in Landau levels, thus, population inversion condition in this case requires more particles on the *lower* levels - this condition is satisfied by the one dimensional distribution of particles in pulsar magnetosphere. The cyclotron-Cherenkov emission is not new in astrophysics: it is exactly by this resonance that cosmic rays produce Alfvén wave in the interstellar shocks. In addition, the laboratory devices called Slow Wave Electron Cyclotron Masers use this resonance to produce high power microwave emission.

Emission of a charged particle propagating *in a medium with a curved magnetic field* differs from conventional Cherenkov, cyclotron or curvature emission and includes, to some extent, the features of each of these mechanisms. We have developed a formalism for considering an emissivity of a particle in a curved field in a medium (Lyutikov, Machabeli & Blandford 1999a). The resulting process may be called a coherent curvature emission. The Cherenkov-drift instability that operates in pulsars is related to some low frequency electromagnetic instabilities in TOKAMAKs; the ultrarelativistic energies in pulsars change it to a high frequency one.

Both instabilities develop in a limited region on the open field lines at large distances from the surface $r \approx 10^9$ cm. The size of the emission region is determined by the curvature of the magnetic field lines, which limits the length of the resonant wave-particle interaction and growth of the wave. The location of the cyclotron-Cherenkov instability is limited to the field lines with large curvature, while the Cherenkov-drift instability occurs on the field lines with the radius of curvature limited both from above and from below. There are two possible locations of the Cherenkov-drift instability: in a ringlike region around the straight field lines and in the region of swept back field lines (Fig. 1). Thus, both instabilities produce narrow pulses, though they operate at radii where the opening angle of the open field lines is large.

The proposed theory is capable of explaining many observational results:

- Energetic: approximately 1% of the beam energy is transfered into radiation

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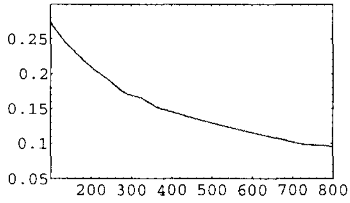
- Waves are emitted approximately half way through the light cylinder; curvature of filed lines controls the emission regions (cyclotron absorption may also be important)
- Radius-to-frequency mapping for core $r \propto \nu^{-1/6}$
- Width-frequency dependence is controlled by the combination of the growth rate of the instability and the structure of the field line



- Fundamental modes are linearly polarized
- Different distribution function of secondary electrons and positrons results in circular polarization for some $\theta < \theta^*$. For the resonance on the beam the circular polarization reaches maximum in the center. For the resonance on the tail particles the sense of the polarization changes due to the curvature drift.
- Higher degree of circular polarization at high frequencies: higher frequencies resonate only with the beam, lower frequencies can resonate with the tail particles where both types of charges are present.
- Spectra of the core emission are controled by the quasilinear diffusion, which gives a spectral index $\alpha = -2$ (Lyutikov 1998a) . Other nonlinear processes, like Raman scattering (Lyutikov 1998b) may also be important.

- Large emitting size and high altitudes (Gwinn et al. 1997, Smirnova et al. 1995, Kijak & Gil 1998)
- High energy emission: development of the cyclotron instability excites gyration; reemission on the normal Dopper resonance boosts the frequency into the optical-UV-soft X-ray region $\omega \sim \omega_B \gamma$.

One of the most challenging consequences of our model is that emission is generated at high altitudes. Below we list both observational and theoretical arguments that support this:

- "Wide beam" geometry: correlation in intensity and position angle in widely separated pulses (Manchester 1995)
- Emission bridge between some widely separated pulses
- Extra peaks in Crab at high frequencies
- Alignment of Radio and High Energy emission in Crab and partially in Vela
- Large emission size of Vela (500 km) (Gwinn et al. 1997) (also Smirnova et al. 1995, Kijak & Gil 1998)
- For small r typical plasma frequencies $\omega_p, \omega_B \gg \omega$ (Kunzl et al. 1998); excitaion of wave with $\omega \ll \omega_p$ is impossible (Lyutikov 1999b)

Predictions of our model are:

- "frequency incoherent maser": at each moment emission consists of narrow frequency features
- increase of circular polarization with frequency (at higher frequencies the cyclotron instability on the beam with one sign of charge dominates over cyclotron instability on the tail particles, where both signs of charge present)
- linear polarization of cone $\perp$ to $\mathbf{B}$ plane (may be resolved using interstellar scintillations similar to Smirnova et al. 1996)

The weak points of the model are: (i) the development of the cyclotron instability requires that the plasma be relatively dense and slow streaming ($\gamma_p \approx 10$) - this is unusual but not unreasonable; (ii) width-period dependence - now it is determined not only by the geometrical factors, but also by the plasma parameter (growth rates).

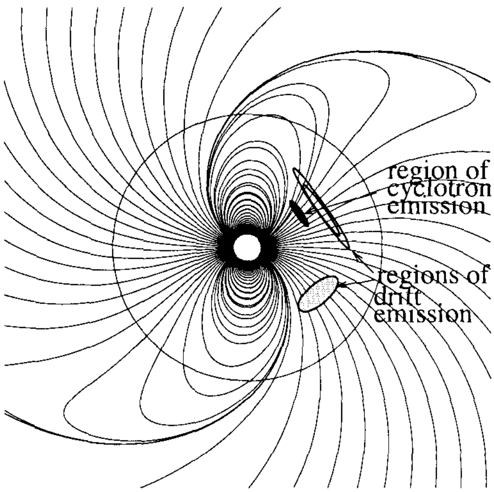


Figure 1. Location of the emitting regions

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