Chin. J. Astron. Astrophys. Vol. 6 (2006), **Suppl. 2**, 81–84
(*http://www.chjaa.org*)

Chinese Journal of
Astronomy and
Astrophysics

A Mechanism For The Reversible Radio Emission in PSR B1822–09

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Abstract We discuss a possible scenario that allows explanation of the anti-correlation between MP sand IP of PSR B1822–09. We assume that the working regime of the inner gap is influenced by the outer gap. Depending on the surface temperature of the polar cap, one can expect alteration of the mean Lorentz factors of the secondary particles, which drastically affects the radio emission process. We also propose the model of generation of the coherent radio emission in reversible direction, toward the neutron star. The model is based on the resonant interaction of plasma clouds, created by gamma rays radiated in inner and outer gaps.

Key words: pulsars: radio emission — individual PSR B1822–09

1 INTRODUCTION

A model for PSR B1822–09 was recently proposed by Dyks, Zhang & Gil (2005), which implies the reversals of radio emission direction to explain the MP and IP behavior. Here we propose the model of generation of such coherent radio emission. The model is based on the resonant interaction of plasma clouds, created by gamma rays radiated in inner and outer gaps. We assume that there are two regions in the pulsar magnetosphere where high energy photons can be converted into e^-e^+ pairs: the polar gap and outer gap. In the polar gap the pair creation process develops either in the sparking regime or in the steady flow regime. The interaction of high energy photons (emitted by the particles accelerated in the outer gap) with the thermal X-rays also results in e^-e^+ pair production. Those pairs move towards the neutron star. The interaction of back streaming particles with the plasma flowing from the polar gap can produce a turbulence of Langmuir waves via the two-stream instability. The radio emission can be produced by the coherent curvature emission of the charged solitons (Gil, Lyubarsky & Melikidze 2004).

2 RADIATION PHYSICS

Although there is no general agreement as to what actual physical mechanisms are responsible for generation of the observed coherent pulsar radio emission, some ingredients seem to be commonly accepted. First of all, a relatively dense, quasi-neutral electron-positron plasma is needed. Such a secondary plasma can be produced by cascading processes in the strong magnetic field by ultrarelativistic charged particles, accelerated in the inner and/or outer vacuum gaps (e.g. Ruderman & Sutherland 1975; Cheng, Gil & Zhang 1998 and references therein). The inner gap can operate either in the nonstationary sparking regime or in the stationary quasi-still regime while the outer gap can only work in the quasi-still regime. Both gaps can produce relativistic electron-positron pairs, so potentially there can be two streams of secondary plasma in a magnetosphere of a given pulsar: the outward (streaming towards the light cylinder) plasma created by the inner gap particles and the inward (streaming towards the neutron star) plasma created by the outer gap particles. The energy of these two components depends on the conditions within the considered gaps. When one gap is very active in producing a copious amount of pairs, usually the other one should be screened out

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and set non-active. However, it can happen that both inner and outer gaps are working along the same sets of magnetic field lines in some kind of a quasi-equilibrium mutually interfering regime.

An important aspect of pulsar radiation physics is a two-stream instability which occurs when a plasma is penetrated by the beam of charged particles (for a detailed discussion of the two-stream instability in pulsar see Asseo & Melikidze 1998). The instability generates the Langmuir waves, which can form a low frequency charge modulation (a charged soliton) and therefore emit a coherent curvature radiation. Such a mechanism was proposed for the observed pulsar radio emission by Melikidze, Gil & Pataraya 2000), who explored a nonstationary inner vacuum gap discharging by short lived sparks proposed originally by Ruderman & Sutherland (1975). In their model, the two-stream instability is caused by overlapping the charged particles with different momenta from plasma clouds associated with consecutive sparks. The charged turbulence formed by the modulational instability can emit coherent curvature radiation at radio wavelengths. As shown by Gil, Lybarski & Melikidze (2004), this model provides a very plausible mechanism of generation of the observed pulsar radio emission. The outgoing radiation is emitted outward the neutron star and is polarized perpendicularly to the planes of dipolar magnetic field lines. Thus the waves can escape from the magnetosphere without damping.

3 THE WAVES

The electron-positron plasma differs from the electron-ion plasma by lack of gyrotropy. Consequently, spectra of waves propagating in the e^-e^+ plasma are simpler than the spectra of waves in the electron-ion plasma. It consists of only two types of waves (called t and lt modes or extra-ordinary and ordinary modes) corresponding to two planes of polarization. The lt-modes are polarized in the plane of the wave-vector $\mathbf{k}$ and local magnetic field $\mathbf{B}$, while the t-modes are polarized orthogonally to $\mathbf{kB}$-plane. The dispersion of the low frequency t-waves can be written as:

$$\omega = kc\,(1-\delta)\,, \tag{1}$$

where $\delta = \frac{\omega_{\rm p}^2}{4\omega_B^2\gamma_{\rm p}^3}$, $\omega_{\rm p} = (4\pi e^2 n_{\rm p}/m_e)$ is the plasma frequency, $\omega_B = eB/m_e c$ is the electron cyclotron frequency, $n_{\rm p}$ and $\gamma_{\rm p}$ are the plasma number density and the average Lorentz factor of plasma particle, correspondingly. The electric field of lt-waves possesses a component along the external magnetic field. Hence, lt-waves cause the charge-separation along the magnetic field. Thus, they are longitudinal-transverse waves. The group velocity of lt-waves is directed along the magnetic field. In fact, these waves are ducted along the curved magnetic field lines, preserving direction of the wave-vector and cannot escape from the plasma. The electric field vector of the t-waves is always orthogonal to both wave and local magnetic field vectors. Therefore, these waves do not cause the charge separation along the magnetic field line and they are purely transverse waves. The group velocity of t-waves is directed along the wave vector. Therefore, t-waves are the most appropriate waves for explanation of the pulsar radiation.

4 MP - IP ANTICORRELATION MECHANISM

Let us now assume that the surface temperature in the polar cap rises close to the so-called critical value, at which the inner gap becomes largely screened (e.g. Gil, Melikidze & Geppert 2003) and at the same time the outer gap turns to be more active in producing an inward streaming plasma. Then the two-stream instability can develop, due to mutual penetration of outward and inward plasma streams. The power of the coherent curvature radiation depends critically on the Lorentz factor the resonant particles. Thus, if the inward plasma is dominating, the radiation will be emitted towards the neutron star. This can explain a reversal of radio emission, provided that the geometrical conditions are favorable to detect the inward radiation. The above scenario is also valid when the inner gap works in the quasi-still regime producing a stationary plasma flow. The qualitative short description above is supported by detailed calculations of growth rates and efficiencies, which will be published in a forthcoming paper.

5 THE REVERSIBLE RADIO EMISSION

Though, t-waves are the most suitable candidates for the observed emission, some difficulties appear while treating excitation mechanisms for t-waves. The difficulty is caused by the presence of a very strong magnetic field. Direct excitation of t-waves is possible only at high altitudes, where the magnetic field is weaker

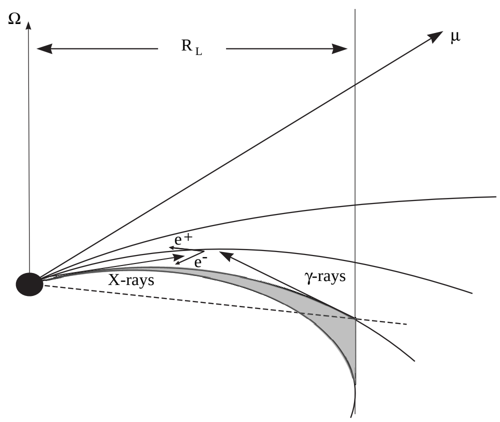

Fig. 1 Geometry of inner and outer gaps in PSR B1822–09. Ω and μ are rotational and magnetic axes respectively. The shadowed region represents the field lines where the outer gap exists.

and particles can poses momenta across the field lines. Two instabilities are able to excite t-waves: cyclotron instability and Cherenkov-drift instability (Kazbegi, Machabeli & Melikidze 1991a, b). Both of them need resonant particles moving across the magnetic field lines. Then those particles can interact with the electric field of t-waves, providing energy exchange between particles and waves. The relativistic particles while moving along the curved magnetic field lines undergo the curvature drift phenomena. The value of the drift velocity is crucial for the instabilities and it can be estimated as:

$$\frac{u_{\rm d}}{c} = \frac{\gamma c}{\omega_B R_B} \simeq 3 \times 10^{-8} \left(\frac{r}{R_{\rm L}}\right)^{2.5} \gamma. \tag{2}$$

Here R_B is the curvature of the magnetic field lines, $R_{\rm L}$ is a light cylinder an r is an altitude. The growth rate of the cyclotron instability is sensitive to the parameter δ (see Equation (1)) which equals to:

$$\delta \simeq 2 \times 10^{-3} \left(\frac{r}{R_{Lc}}\right)^{2.5} \frac{\kappa}{\gamma_{\rm p}^3}. \tag{3}$$

Here κ is the Sturrock (1971) multiplication factor. Now we can estimate the growth rate of the cyclotron instability as:

$$\Gamma_{\rm cyc} \simeq 10^{-6} \left(\frac{r}{R_{\rm L}}\right)^3 \frac{\kappa}{\gamma_{\rm p}^3 \gamma_0} \quad \text{if} \quad \left(\frac{u_{\rm d}}{c}\right)^2 \ll 2\delta \tag{4}$$

and

$$\Gamma_{\rm cyc} \simeq 10^{-14} \left(\frac{r}{R_{\rm L}}\right)^5 \frac{\kappa \gamma_{\rm p} \gamma_{\rm r}^2}{\gamma_0} \quad \text{if} \quad \left(\frac{u_{\rm d}}{c}\right)^2 \gg 2\delta. \tag{5}$$

Here $\gamma_{\rm r}$ and γ_0 are the Lorentz factor and the thermal spread of the resonant particles. The necessary condition for the instability to be developed is $\Gamma \gg c/r$, which follows from the requirement that the characteristic time for the instability development should be much less than time necessary for the plasma to escape from the light cylinder. Hence, in the pulsar magnetosphere the cyclotron instability can develop at the relatively high altitudes $r \simeq 0.5 R_{\rm L}$, providing that the average Lorentz factor of plasma particles is about $\gamma_{\rm p} \sim 3$.

The growth rate of the Cherenkov-drift instability is proportional to $u_{\rm d}^2$ and can be estimated as

$$\Gamma_{\rm CD} \simeq 10^{-18} \left(\frac{r}{R_{\rm L}}\right)^6 \frac{\gamma_{\rm r}^4}{\gamma_{\rm p} \gamma_0^{1/2}} \kappa^{1/2}. \tag{6}$$

It is clear that the favorable conditions for its development can be found at the high altitudes.

Therefore, the most plausible radiation mechanism should be the coherent curvature radiation. The reversible radio emission can naturally exist if there is a mechanism for excitation of longitudinal waves propagating toward the neutron star. Such a mechanism can be the two-stream instability developed by interaction of back and forth streaming plasma flows.

The instability can be studied by means of the dispersion equation of one dimensional plasma. We assume that the Langmuir waves propagate strictly along the magnetic field as well as plasma particles ($k = k_{\|}$ and $p = p_{\|}$). In this approximation the dispersion equation writes:

$$k^2c^2 - \omega_{\mathrm{p}1}^2 \int \frac{f_1(p)}{\gamma^3} \frac{dp}{(v_\phi - v)^2} - \omega_{\mathrm{p}2}^2 \int \frac{f_2(p)}{\gamma^3} \frac{dp}{(v_\phi - v)^2} = 0. \tag{7}$$

Here $v_\phi = \omega/kc$; v and p are dimensionless velocity and momentum of particles. The subscribes '1' and '2' describe particles moving towards the star and the light cylinder correspondingly. It is easy to show that in this case the growth rate of the unstable Langmuir perturbations writes:

$$\frac{\Gamma}{\omega_0} \approx \left(4\frac{\gamma_2^3}{\gamma_1^3}\frac{\omega_{\mathrm{p}1}^2}{\omega_{\mathrm{p}2}^2}\frac{1}{\gamma_\phi}\right) \ \text{and} \ \omega_0 \approx kc \approx \omega_{\mathrm{p}2}\frac{1}{2\gamma_2^{1.5}}. \tag{8}$$

Here $\gamma_\phi = \left(1 - v_\phi^2\right)^{0.5} \approx \gamma_1$ and ω_0 is the real part of ω. Applicability conditions of Equation (8) are as follows:

$$1 \gg \frac{\Gamma}{\omega_0} \gg \left(4\frac{\gamma_2^3}{\gamma_1^3}\frac{\omega_{\mathrm{p}1}^2}{\omega_{\mathrm{p}2}^2}\right)^{0.5} \ \text{and} \ \frac{\Gamma}{\omega_0} \gg \frac{1}{2\gamma_\phi^2}. \tag{9}$$

Now we need to define a domain of parameters where the instability can develop. The basic parameters of PSR B1822–09 are as follows: the dipole field at the stellar surface $B_0 = 1.3 \times 10^{13}$ G, the Goldreich-Julian number density (at the stellar surface) $n_0 = 6 \times 10^{11}$ cm^{-3}, the spin-down energy loss $L_{\mathrm{sd}} = 4.6 \times 10^{33}$ erg s^{-1}, the radio luminosity $L_{\mathrm{r}} = 10^{26}$ erg s^{-1}. It should be mentioned that the efficiency of radio-emission is extremely low, only about 3×10^{-8} portion of the spin-down energy loss is converted into observed radio-emission. Most pulsars with such a low efficiency radiate a high-energy radiation also.

We assume that the fluxes of particles in both directions are about the same: $n_1\gamma_1 \approx n_2\gamma_2$. At the altitude about 50 stellar radii from the surface we can estimate the parameters as follows: $\omega_{\mathrm{p}1} \approx 5 \times 10^{10}$, $\gamma_1 \approx 500$, $\omega_{\mathrm{p}2} \approx 5 \times 10^9$, $\gamma_2 \approx 5$. Such parameters can be realized when the inner gap discharge is in the steady regime. Then we can expect a high multiplication factor about 10^5. Then the instability has enough time to develop. The corresponding condition writes: $c/\Gamma \ll 5 \times 10^7$ cm. The radio emission is generated according to the scenario described by Gil, Lyubarsky & Melikidze (2004). As we can see from Equations (8) and (9) the reversal wave generation is sensitive to the Lorentz factors of the plasma flows. Therefore, if the inner gap operates in the sparking regime, we can expect γ_2 to be much higher (about 100) and then the inward wave generation does not occur.

Acknowledgements We acknowledge the support of the Polish State Committee for scientific research under Grant 2 P03D 029 26. GM was partially supported by Georgian NSF grant ST06/4-096.

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