THE SYNCHROTRON EMISSION MECHANISM IN THE RECENTLY DETECTED VERY HIGH ENERGY RADIATION FROM THE CRAB PULSAR

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ABSTRACT

Interpretation of the recently discovered very high energy (VHE) pulsed emission from the Crab pulsar is presented. By taking into account the fact that Crab pulsar’s radiation for the optical and VHE spectrum peak at the same phases, we argue that the source of this broadband emission is spatially localized. It is shown that the only mechanism providing the results of the MAGIC Cherenkov telescope should be synchrotron radiation. We find that in the magnetospheric electron–positron plasma, due to the cyclotron instability, the pitch angle becomes non-vanishing, which leads to an efficient synchrotron mechanism, intensifying on the light cylinder length scales. We also estimate the VHE radiation spectral index to be equal to $-1/2$.

Key words: instabilities – plasmas – pulsars: individual (PSR B0531+21) – radiation mechanisms: non-thermal

1. INTRODUCTION

One of the fundamental problems concerning pulsars relates to the origin of the high-energy electromagnetic radiation. According to the standard approach, two major mechanisms govern the high-energy radiation: inverse Compton scattering (e.g., Blandford et al. 1990) and synchrotron emission (Pacini 1971; Shklovsky 1970). To date, in most cases it is not clear where the location of the high-energy electromagnetic radiation is: closer to the pulsar (polar-cap model, see for example, Sturrock 1971) or farther out in the magnetosphere (outer-gap model, see for example, Cheng et al. 1986a, 1986b). An exception is the high-energy emission recently detected by the MAGIC Cherenkov telescope (Aliu et al. 2008), which has revealed that the pulsed radiation above 25 GeV is inconsistent with polar-cap models. In the framework of these models, over the star’s surface there is a vacuum gap with an electric field inside (Ruderman & Sutherland 1975), which accelerates particles up to relativistic energies leading to the emission process. Unfortunately, the energies of the particles accumulated in the gap are not enough to explain the observed radiation. To solve this problem several mechanisms have been proposed. To increase the gap size, Usov & Shabad (1985) considered the formation of positronium (electron–positron bound state). Another mechanism, leading to the enlargement of the gap zone was introduced by Arons & Scharlemann (1979) and apply the method to the Crab pulsar. For this purpose we use the approach developed in (Machabeli & Usov 1979) and apply the method to the Crab pulsar.

The Letter is organized as follows. In Section 2, we consider the synchrotron radiation of electrons, in Section 3 we present our results, and in Section 4 we summarize them.

2. SYNCHROTRON EMISSION

According to the theory of synchrotron emission, a relativistic particle moving in a magnetic field emits electromagnetic waves with the following photon energies (e.g., Rybicki & Lightman 1979):

$$\epsilon \approx 1.2 \times 10^{-17} B \gamma^2 \sin \psi \text{ (GeV)},$$

(1)

where $B$ is the magnetic induction, $\gamma$ is the Lorentz factor, and $\psi$ is the pitch angle. On the other hand, for typical magnetospheric parameters the timescale of the transit to the ground Landau state is so small that almost from the very beginning of motion, electrons move quasi-one-dimensionally along the field lines.
without emission. The situation changes due to the cyclotron instability of the electron–positron magnetospheric plasma, which “creates” certain pitch angles, leading to the subsequent emission process (Machabeli & Usov 1979). In this Letter, we consider a plasma composed of two components: (1) a plasma component with the Lorentz factor, \(\gamma_p\), and (2) a beam component with the Lorentz factor, \(\gamma_b\). According to the approach developed by Machabeli & Usov (1979), due to the quasi-linear diffusion the following transverse and longitudinal–transversal waves are generated:

\[
\omega_t = k_c \left( 1 - \frac{\omega_p^2}{4\omega_b^2\gamma_p^3} \right), \quad (2)
\]

\[
\omega_l = k_c \left( 1 - \frac{\omega_p^2}{4\omega_b^2\gamma_p^3} - \frac{k_t^2c^2}{16\omega_b^2\gamma_p} \right). \quad (3)
\]

Here, \(k\) is the modulus of the wave vector, \(k_t\) and \(k_l\) are the wave vector’s longitudinal (parallel to the background magnetic field) and transverse (perpendicular to the background magnetic field) components, respectively, \(c\) is the speed of light, \(\omega_p \equiv \sqrt{4\pi n_p e^2/m}\) is the plasma frequency, \(\omega_B \equiv eB/mc\) is the cyclotron frequency, \(e\) and \(m\) are the electron’s charge and the rest mass, respectively, and \(n_p\) is the plasma density.

For generation of the aforementioned modes, the cyclotron resonance condition (Kazbegi et al. 1992),

\[
\omega - k_t V_t - k_u u_t \mp \frac{\omega_B}{\gamma_B} = 0, \quad (4)
\]

has to be satisfied. Here, \(u_t \equiv cV_t\gamma_B/\rho\omega_B\) is the drift velocity of resonant particles, \(V_t\) is the component of velocity along the magnetic field lines, and \(\rho\) is the curvature radius of the field lines.

When a particle moves along a curved magnetic field line it experiences a force that is responsible for the conservation of the adiabatic invariant, \(I = 3cp^2/2eB\) (Landau & Lifshitz 1971). The transverse and longitudinal components of the aforementioned force are given by the following expressions:

\[
G_{\perp} = -\frac{mc^2}{\rho}\gamma_B\psi, \quad G_{\parallel} = \frac{mc^2}{\rho}\gamma_B\psi^2. \quad (5)
\]

Since the particle emits \((\lambda < n_p^{-1/3})\) in the synchrotron regime, the corresponding radiative force will appear (Landau & Lifshitz 1971):

\[
F_{\perp} = -\alpha\psi(1 + \gamma_B^2\psi^2),
\]

\[
F_{\parallel} = -\alpha\gamma_B^2\psi^2, \quad \alpha = \frac{2e^2\omega_B^2}{3c^2}. \quad (6)
\]

On the other hand, if one assumes Equations (2)–(4), then one can show that for all frequencies in the optical range \((\sim 10^{15}\ Hz)\), the development of the cyclotron instability occurs from the distances of the order of the light cylinder radius, \(R_L\) (Machabeli & Usov 1979). We have used the parameters: \(P \approx 0.033\ s, \quad R_L \approx 10^8\ cm, \quad n_p \approx 1.4 \times 10^{19}\ cm^{-3}, \quad B_L \approx 7 \times 10^{12}\ G, \quad \text{and} \quad \gamma_b \approx 10^8\). Here, \(P\) is the pulsar’s period, \(R_L\) its radius, and \(n_p\) and \(B_L\) are the plasma density and the magnetic field induction, respectively, close to the star.

These two forces \((F_{\perp}\text{ and } G_{\perp})\) tend to decrease the pitch angle of the particle. In contrast, the quasi-linear diffusion, arising through the influence of the generated waves back on the particles, tries to widen the range of the pitch angles. The dynamical process saturates when the effects of the above mentioned forces are balanced by the diffusion. For \(\gamma\psi \gg 1\) it is easy to show that for typical magnetoplasma parameters the forces satisfy \(G_{\perp} \ll F_{\perp}\) and \(G_{\parallel} \ll F_{\parallel}\). Then, assuming the quasi-stationary case \((\partial/\partial t = 0)\), the corresponding kinetic equation can be presented in the following way (Malov & Machabeli 2001):

\[
\frac{\partial}{\partial t} \frac{f}{p_i} + \frac{1}{p_i\psi} \frac{\partial}{\partial \psi} \left( \frac{\partial^2}{\partial \psi^2} \left( D_{\perp} \frac{\partial f}{\partial \psi} \right) \right) + \frac{1}{p_i\psi} \frac{\partial}{\partial \psi} \left[ \psi \left( D_{\perp} \frac{\partial f}{\partial \psi} + D_{\parallel} \frac{\partial f}{\partial \psi} \right) \right] = 0, \quad (7)
\]

where \(f = f(\psi, p_i)\) is the distribution function of particles, \(p_i\) is the longitudinal momentum,

\[
D_{\perp} \approx -\frac{\pi e^2 n_p c}{\omega}, \quad D_{\parallel} \approx \frac{\pi e^2 n_b\omega_B}{2mc^2\gamma_b}. \quad (8)
\]

are the diffusion coefficients, and \(n_b \equiv \frac{\rho}{\rho_e}\) is the density of the beam component. By expressing the distribution function as \(\chi(\psi) f(p_i)\), one can solve Equation (8) (Malov & Machabeli 2002; Chkheidze & Machabeli 2007):

\[
\chi(\psi) = C_1 e^{-A\psi^4}, \quad f(p_i) = \frac{C_2}{(\alpha\psi^2\gamma_B^2 - \frac{\pi e^2\gamma_b}{\gamma_B})}, \quad (9)
\]

where

\[
A \equiv \frac{4e^6 B^4 P^3 \gamma_B^4}{3\pi^3 m^3 c^4 \gamma_B}. \quad (10)
\]

and

\[
\psi = \frac{\int_0^\infty \chi(\psi) d\psi}{\int_0^\infty \chi(\psi) d\psi} \approx 0.5. \quad (11)
\]

is the mean value of the pitch angle. In the expression of \(f(p)\) which is responsible for the synchrotron radiation spectrum (see discussion), the first term in the denominator comes from the synchrotron reaction force, and the second term is the contribution of the quasi-linear diffusion.

After combining Equation (11) with Equation (1) one gets the following expression of energy of the synchrotron photons:

\[
\epsilon(GeV) \approx 6 \times 10^{-18} \left( \frac{3\pi^3 m^5 e^3 \gamma_p^4}{4P^3 e^6 \gamma_p^4} \right)^{1/2}. \quad (12)
\]

3. DISCUSSION

As we have discussed, a typical distance where the instability develops, is of the order of the light cylinder radius, \(\sim 10^8\) cm. In this area, due to quasi-linear diffusion, a pitch angle (see Equation (11)) is created, leading to synchrotron radiation.

Let us consider Equation (12) for the Crab pulsar and assume that the Lorentz factor of the plasma component is of the order of \(\sim 3\) (Machabeli & Usov 1989). In Figure 1, we show the dependence of the emission energy on the Lorentz factor of the beam component. The set of parameters is \(R_L \approx 10^6\ cm, \quad B_L \approx 7 \times 10^{12}\ G, \quad \text{and} \quad \gamma_p \approx 3\). As is seen from the figure, the high-energy emission of the order of 25 GeV is possible for
γ_b ≈ 3.2 × 10^8. This in turn implies that the gap models providing the Lorentz factors ∼10^7, are not enough to explain the detected pulsed emission of the Crab pulsar. One of the possibilities could be the centrifugal acceleration of particles, when due to the frozen-in condition, electrons move along the co-rotating magnetic field lines and accelerate centrifugally (Machabeli & Rogava 1994; Rogava et al. 2003; Osmanov et al. 2007). An alternative mechanism for explaining the observed high-energy radiation could be a collapse (e.g., Artsimovich & Sagdeev 1979; Zakharov 1972) of the centrifugally excited unstable Langmuir waves (Machabeli et al. 2005) in the pulsar’s magnetosphere. Such a possibility was shown by Machabeli et al. (2002, 1999) for an electron–positron plasma.

If we take γ_b ≈ 3.2 × 10^8 into account, after substituting all necessary parameters into Equation (11), we can show that the created (via the quasi linear instability) pitch angle is of the order of 10^{-3}. This, in turn, confirms our assumption γ_bψ ≫ 1, which has been used for constructing and solving Equation (8). The timescale of the synchrotron emission is still very small and the electrons pass very soon to the ground Landau state and, therefore, the distribution function becomes one dimensional. Such a distribution function is unstable against the anomalous Doppler effect and excites optical radiation. This mode simultaneously leads to quasi-linear diffusion, which, in creating the pitch angles, produces high-energy (>25 GeV) emission. The synchrotron radiation reaction force limits the pitch angles that saturate due to the balance between the mentioned forces and the corresponding diffusion effects. On the other hand, the credibility of the present mechanism comes from the observationally evident coincidence of the optical and high-energy spectrum phases.

We see that synchrotron emission can explain the detected coincidence of the optical and VHE emission phases in terms of the quasi-linear diffusion. However, it is supposed that apart from the synchrotron process, the inverse Compton mechanism and the curvature radiation can also be responsible for the emission in the pulsar magnetospheres. But if this is the case, then the area of the inverse Compton and the curvature radiation must be stretched and not localized, leading to relative shifts of phases, contrary to the observational pattern.

The expression of f(p_e) gives a possibility to predict the observed spectrum of the synchrotron emission. Indeed, one can easily show that for the Crab pulsar’s magnetospheric parameters with γ_b ∼ 3.2 × 10^8 and ψ ∼ 10^{-5}, one has α2γ_b^2ψ_nbc/γ_b ∼ π2e^2ψ_nbc/γ_b. Then the distribution function behaves as f(p_e) ∝ γ^{-2}. On the other hand, according to the well known power-law formula, the spectrum of the synchrotron radiation is given by I_ν ∝ ν^{-2+4α} (Ginzburg 1981), where β describes the particle distribution function, f ∝ γ^{-β}. Therefore, in our case (β = 2) the spectral index of synchrotron emission is −1/2.

4. SUMMARY

1. Considering the recently detected VHE emission from the Crab pulsar, we studied the role of the synchrotron mechanism in producing the observed high energies.

2. We emphasized that due to very small cooling timescales, particles rapidly transit to the ground Landau state, preventing subsequent radiation. The situation changes thanks to the cyclotron instability, which at a certain distance from the star’s surface develops efficiently and creates non-vanishing pitch angles, leading to an efficient synchrotron emission process with spectral index −1/2.

3. Since the cyclotron instability generates the optical spectrum and provokes the increase of the pitch angle, we argue that the emission in the aforementioned low (optical) and high (25 GeV) energy intervals originates from well localized regions, leading to the observed fact that the signals peak with the same phases. This in turn means that inverse Compton scattering and curvature radiation must be excluded from the consideration and the only mechanism providing VHE γ-rays is synchrotron emission.

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REFERENCES

Aliu, E., et al. 2008, ApJ, 674, 1037A

Arons, J., & Scharlemann, E. T. 1979, Apl, 231, 854

Artsimovich, L. A., & Sagdeev, R. Z. 1979, Plasma Physics for Physicists (Russian edition; Moscow: Atomizdat)

Blandford, R. D., Netzer, H., & Woltjer, L. 1990, Active Galactic Nuclei (Berlin: Springer)

Cheng, K. S., Ho, C., & Ruderman, M. 1986, ApJ, 231, 854

Cheng, K. S., Ho, C., & Ruderman, M. 1986, ApJ, 300, 522

Chkhaidze, N., & Machabeli, G. 2007, 471, 599

Ginzburg, V. L. 1981, Teor. Fiz. Astrofiz. (Moscow: Nauka)

Harding, A. K., Stern, J. V., Dyks, J., & Frackowiak, M. 2008, ApJ, 680, 1378

Kazbegi, A. Z., Machabeli, G. Z., & Melikidzem, G. I. 1992, in Proc. IAU Colloq. 128, The Magnetospheric Structure and Emission Mechanisms of Radio Pulsars, ed. T. H. Hankins, J. M. Rankin, & J. A. Gil (Zielona Gora: Pedagogical Univ. Press), 232

Landau, L. D., & Lifshitz, E. M. 1971, Classical Theory of Fields (London: Pergamon)

Machabeli, G. Z., Luo, Q., Vladimirov, S. V., & Melrose, D. B. 2002, Phys. Rev. E, 65, 036408

Machabeli, G., Osmanov, Z., & Mahajan, S. 2005, Phys. Plasmas, 12, 062901

Machabeli, G. Z., & Rogava, A. D. 1994, Phys. Rev. A, 50, 98

Machabeli, G. Z., & Usov, V. V. 1979, Pis’ma Astron. Zh., 5, 445

Machabeli, G. Z., & Usov, V. V. 1989, Pis’ma Astron. Zh., 15, 910

Machabeli, G. Z., Vladimirov, S. V., & Melrose, D. B. 1999, Phys. Rev. E, 59, 4552

Malov, I. F., & Machabeli, G. Z. 2001, ApJ, 554, 587

Malov, I. F., & Machabeli, G. Z. 2002, Astron. Rep., 46, 684

Manchester, R. N., & Taylor, J. H. 1980, Pulsars (San Francisco, CA: Freeman)
Muslimov, A. G., & Tsygan, A. I. 1992, MNRAS, 255, 61
Osmanov, Z., Rogava, A. S., & Bodo, G. 2007, A&A, 470, 395
Pacini, F. 1971, Apl, 163, 117
Rogava, A. D., Dalakishvili, G., & Osmanov, Z. 2003, Gen. Relativ. Gravit., 35, 1133
Ruderman, M. A., & Sutherland, P. G. 1975, Apl, 196, 51
Rybicki, G. B., & Lightman, A. P. 1979, Radiative Processes in Astrophysics (New York: Wiley)
Shklovsky, I. S. 1970, Apl, 159, L77
Sturrock, P. A. 1971, Apl, 164, 529
Usov, V. V., & Shabad, A. 1985, Ap&SS, 117, 309
Zakharov, V. E. 1972, JETP, 35, 908