On the fraction of particles involved in magneto-centrifugally generated ultra-high energy electrons in the Crab pulsar

Osmanov, Z.N. • Mahajan, S.M.

Abstract The earthward journey of ultra high energy electrons ($\sim 600$ TeV) produced in the Pulsar atmosphere by Landau damping of magneto-centrifugally excited Langmuir waves (drawing energy form the rotational slowdown) on primary electrons, is charted. It is shown, that just as they escape the light cylinder zone, the ultra-high energy particles, interacting with the medium of the Crab nebula, rapidly loose their energy via the quantum synchrotron process, producing highly energetic gamma rays $\sim 0.6$ PeV. Interacting with the cosmic background radiation in the interstellar medium, only a tiny fraction of these ultra high energy photons (via the $\gamma\gamma$ channel) are, then transformed into electron-positron pairs. Detected flux of these photons imposes an upper limit on the fraction $(4 \times 10^{-7})$ of the magnetospheric particles involved in the process of generation of ultra-high energy photons (up to 600 TeV).

Keywords

1 Introduction

A theoretical framework for particle acceleration, driven by the rotational slow down of a pulsar, has been proposed in which the star rotational energy is channelled for particle acceleration. We have concentrated on the Crab pulsar whose rotational slowdown is the fundamental energy source that is channelized for particle acceleration.

Before working out the details of the dynamics of the PeV electrons, we would summarize the detailed dynamics that led to the creation of such energetic particles. We have concentrated on the Crab pulsar whose rotational slowdown is the fundamental energy source that is channelized for particle acceleration.

The crab pulsar - a rapidly rotating neutron star is a most interesting astrophysical object characterized by relatively high angular velocities of rotation. Belonging to the class known as millisecond pulsars, its rotation period $P \approx 0.0332$ s, is decreasing at the rate $\dot{P} = dP/dt \approx 4.21 \times 10^{-13}$ s$^{-1}$. The corresponding energy released per second, as a result of the slowdown, is enormous: $\dot{W} \approx I\Omega^2d\Omega/dt \approx 5 \times 10^{38}$ erg/s, where $I = 2/5M R_{\ast}^2$ is the moment of inertia of the Crab pulsar, $M \sim (1.5 - 2.5) \times M_\odot$ is its mass, $M_\odot \approx 2 \times 10^{33}$ g is the solar mass, $R_{\ast} \approx 10$ km is the neutron star’s ra-
radius and $\Omega \equiv 2\pi/P$ is the pulsar’s angular velocity of rotation. It is worth noting that only a tiny fraction of the total energy goes through the pulsar channel, approximately 40% is radiated by the nebula and the rest is lost in unknown ways.

In the framework of the standard pulsar model \cite{Deutsch1955, Goldreich1969}, the magnetosphere is fed by the electrons uprooted from a neutron star’s surface by means of the longitudinal component (along the magnetic field lines) of the electrostatic field. In due course of time these particles accelerate and start emitting radiation because of the nonzero curvature of field lines. It is strongly believed that the photons inevitably reach the threshold energy, $2mc^2$ ($m$ is the electron’s mass and $c$ is the speed of light) when they transit to the pair creation channel $\gamma + B \rightarrow e^+ + e^- + \gamma'$ leading to the cascading mechanism; the pair production continues until the magnetospheric plasma electron-positron ($e^+e^-$) plasma screens out the initial electrostatic field. We have discussed in a previous paper that the acceleration inside the gap (augmented by several modifications) is quite inadequate, by itself, to explain the observed high energy emission from the Crab pulsar \cite{Mahajan2013}. Our model of particle acceleration to high energies, the Langmuir Landau — (LLCD) mechanism \cite{Osmanov2021, Machabeli2005}, is a two stage process: 1) the time dependent centrifugal force excites growing electrostatic waves in the electron-positron plasma permeating the pulsar magnetosphere, 2) these waves in turn, very rapidly Landau damp and efficiently accelerate particles to ultra-high energies ($\sim 0.1 – 1$ PeV). The gravitational energy is thus converted to kinetic energy via electric field energy. This process requires initially accelerated electrons, which, by means of the frozen-in condition, will be supported by direct centrifugal mechanism. Charged electrons moving along co-rotating almost straight open magnetic field lines (see Fig. 1) will be energized, attaining large azimuthal velocity close to the light cylinder surface (a hypothetical zone, where the linear velocity of rotation exactly equals speed of light).

Searching for mechanism that may boost particle energies to the PeV range becomes highly relevant in the context of observations of the Fermi-LAT collaboration - in particular, the observations of gamma-ray flares from the Crab pulsar in 2009 and 2010 \cite{Abdo2011}. By analyzing the spectral behaviour of high energy emission in the energy band $> 1$GeV, the authors conclude that electrons must have energies as high as 1 PeV \cite{Abdo2011}.

The new contribution of this paper will consist, primarily, of exploring the possible role of the LLCD accelerated PeV electrons in creating energetic photons. In section 2, we summarize the basic content of LLCD-the basics of electron acceleration, and energy loss/energy conversion mechanisms. In section 3, we work out the action of the accelerated electrons to create the PeV photons, the end product of the processes explored by \cite{Mahajan2013}. The Crab nebula will be our representative millisecond pulsar. In section 4, we summarize our findings and results.

2 Theoretical model

The major results of \cite{Mahajan2013} were obtained in a simple theoretical model in which the field lines are almost rectilinear and the particle distribution corresponds to one in the standard model of pulsars (Fig. 2). Here the narrower area corresponds to the primary beam components and the wider one - to the secondary particles. The linearized system of equations- the Euler, the continuity, and the Poisson equation, governing the two stream instability, then, reduces to the following form \cite{Mahajan2013, Machabeli2005} ($c$ and $m$ are electron charge and rest mass):

\begin{equation}
\frac{dp_\beta}{dt} + ikv_\beta p_\beta = v_\beta \Omega^2 r_\beta p_\beta + \frac{2e}{m} E, \quad (1)
\end{equation}

\begin{equation}
\frac{dn_\beta}{dt} + ikv_\beta n_\beta + i\kappa n_\beta = 0 \quad (2)
\end{equation}

\begin{equation}
iKE = 4\pi e \sum_\beta n_\beta, \quad (3)
\end{equation}

where $\beta = 1, 2$ is the species (electron, positron)index, $p_\beta$ ($n_\beta$) is the perturbed momentum (the number density), $v_\beta \approx V_\beta \cos (\Omega t + \phi)$ and $n_\beta$ are the unperturbed velocity and number density, while $r_\beta \approx \frac{V_\beta}{\Omega} \sin (\Omega t + \phi)$ is the radial coordinate, and $\Omega$ is the angular velocity of rotation. The characteristic wave number of the perturbed electrostatic field $E$ (of the induced Langmuir wave) is denoted by $k$. In what follows, we will recapitulate the salient features of the content of \cite{Osmanov2021, Mahajan2013, Machabeli2005}.

The anzatz

\begin{equation}
n_\beta = N_\beta e^{-\frac{iV_\beta k}{n} \sin (\Omega t + \phi_\beta)}, \quad (4)
\end{equation}

converts Eqs. (1-2) into a pair of coupled, non-autonomous differential equations

\begin{equation}
\frac{d^2N_1}{dt^2} + \omega_1^2 N_1 = -\omega_1^2 N_2 e^{i\chi}, \quad (5)
\end{equation}

\begin{equation}
\frac{dN_2}{dt} = \omega_1 N_1 \quad (6)
\end{equation}

where $\omega_1$ is an angular frequency, $\chi$ is a constant phase shift, and $N_1, N_2$ are the number densities.
Fig. 1 Sketch of the magnetospheric-centrifugal Pulsar model. Charged particles sliding along co-rotating open magnetic field lines will attain a large azimuthal velocity component close to light cylinder surface.

\[ \frac{d^2 N_2}{dt^2} + \omega_2^2 N_2 = -\omega_2^2 N_1 e^{-ix}, \]  

where \( \chi = b \cos(\Omega t + \phi_+), b = 2ck/\Omega \sin \phi_-, 2\phi_\pm = \phi_1 \pm \phi_2 \) and \( \omega_{1,2} \equiv \sqrt{8\pi e^2 n_{1,2}/m\gamma_{1,2}^3} \) and \( \gamma_{1,2} \) are the relativistic plasma frequencies and the Lorentz factors for the stream components. The two species have different Lorentz factors and the corresponding centrifugal forces are different as well. The centrifugal force, however, has a periodic time dependence, and, thus, capable of parametrically driving the electrostatic waves.

A Fourier transform of Eqs. (5,6) leads to the "dispersion relation"

\[ \omega^2 - \omega_1^2 - \omega_2^2 J_0^2(b) = \omega_2^2 \sum_{\mu} J_{\mu}^2(b) \left( \frac{\omega^2}{(\omega - \mu \Omega)} \right)^2, \]  

where \( J_{\mu}(x) \) is the Bessel function. The form of the preceding expression suggests that the system may undergo an instability at the following resonance condition, \( \omega_r = \mu_{\text{res}} \Omega \). In the vicinity of the resonance, \( \omega = \omega_r + \Delta \), the dispersion may be approximated as

\[ \Delta^2 = \frac{\omega_r \omega_2^2 J_{\mu_{\text{res}}}^2(b)}{2}, \]  

implying an imaginary part - the growth rate:

\[ \Gamma = \frac{\sqrt{3}}{2} \left( \frac{\omega_r \omega_2^2}{2} \right)^{1/2} J_{\mu_{\text{res}}}^2(b)^{1/2}, \]  

where \( \omega_r = \omega_1^2 + \omega_2^2 J_0^2(b) \)

Through this centrifugally induced Langmuir instability, the rotation energy is very efficiently pumped from the central engine - the pulsar- to the electric field sustained by the bulk magnetospheric e-p plasma. This is the first step in the acceleration mechanism. In the second step, these waves Landau damp on the much faster primary beam electrons, efficiently accelerating them. The corresponding rate of generation of electrostatic waves is given by (Volokitin et al. 1987)

\[ \Gamma_{LD} = \frac{n \gamma \omega_p}{n_1 \gamma_1^{5/2}}, \]  

where \( \omega_p = \sqrt{4\pi e^2 n/m} \), \( \gamma \) and \( n \) are the plasma frequency, the Lorentz factor and the number density of the species on which the damping occurs.

The most optimum scenario for an overall efficient energy pumping/transfer system is realized when the instability growth and Landau damping rates are large and comparable, \( \Gamma \sim \Gamma_{LD} \). If the instability growth rates were far in excess of Landau damping rates, the waves will not be able to transfer much energy to the
particles. On the contrary, if the Landau damping rates were much larger than the growth rates, the waves will not grow much. In either extreme, there will be very little transfer from the star rotation to the particles.

For the crab pulsar parameters, it was been shown in [Mahajan et al. 2013] that the "optimizing" condition $\Gamma \sim \Gamma_{LD}$ can be satisfied, for example, by the combination $\gamma_2 = 4400$, $\gamma_1 \approx 800$ corresponding to the so-called plasma component with moderate Lorentz factors. Here, $\gamma_1$ is the relativistic factor of electrons and $\gamma_2$ - the Lorentz factor of positrons. On the other hand, from symmetry it is clear that the similar results will be obtained if we interchange electrons and positrons. In addition, the instability is supposed to be efficient in the pulsar’s magnetosphere if the corresponding timescale does not exceed the pulsar’s rotation period. This condition is well satisfied for the aforementioned parameters.

It is essential to probe further into the details of energy transfer from the star rotation into the plasma particles. In the local frame of reference the particles are forced to slide along the magnetic field lines by means of the centrifugal force. Viewed in the laboratory frame, the reaction force $F_{\text{rec}} \approx 2mc\Omega\xi^{-3}$ (Rogava et al. 2000), where $\xi \sim \gamma_{1}^{-1/2}$ (Rieger & Mannheim 2000), driving the particles, becomes infinite on the light cylinder surface. This is a natural result - to preserve rigid rotation, the particle velocity, in this region, must exactly equal the speed of light. Note also that the radial velocity tends to zero, because on the light cylinder the particles can only rotate with the linear velocity $c$. It is clear that the maximum energy gained from the rotator can be estimated as the work done by the reaction force. For all particles involved in the process, the energy gain may be estimated as

$$W \approx n_1\delta V F_{\text{rec}}\delta r,$$

where $\delta V$ is the volume in which the pumping takes place and $\delta r \sim c/\Gamma$ is the corresponding lengthscale. This work is transferred to the beam particles in the same volume, therefore one should equate $W$ with $n_b\delta V c$ leading to the estimated value of the maximum attainable energy of electrons

$$\epsilon \approx \frac{n_1 F_{\text{rec}} \delta r}{n_b}.$$  

Simple estimates show that for $\gamma_2 = 4400$, $\gamma_1 \approx 800$ the primary electrons (beam components) with initial Lorentz factor, $10^7$, will reach energy of the order of $\sim 100$TeV. To arrive at this number, we have invoked the Goldreich-Julian number density $n_{GJ} \approx \Omega(1 - r^2/R_{lc}^2)^{-1}/B/2\pi c e e$ (Ruderman & Sutherland 1975), where $B = B_{st}(R_{st}/R_{lc})^3$ ($B_{st} \approx 6.7 \times 10^{12}$ is the magnetic field close to the neutron star’s surface and $R_{lc} \equiv cP/(2\pi)$ is the light cylinder radius). It is also assumed that energy is uniformly distributed among various magnetospheric "species" of particles, $n_1\gamma_1 \approx n_2\gamma_2 \approx n_{GJ}\gamma_{GJ}$.

When we invoke another combination $\gamma_2 = 2 \times 10^4$, $\gamma_1 \approx 4 \times 10^4$ that satisfies the condition $\Gamma \sim \Gamma_{LD}$, and for which the instability time scale $1/\Gamma$ does not exceed the kinematic timescale, $P$ (insuring efficient energy transfer), the projected electron energy jumps up to $\sim 1.3$PeV. Thus, the centrifugally excited Langmuir waves can readily accelerate electrons to PeV energies in the magnetosphere of the crab nebula.

3 Generation of PeV photons

What phenomena will follow in the wake of ultra high energy (PeV) particles interacting with the strong magnetic fields in the pulsar magnetosphere? Copious synchrotron losses will result-the synchrotron emission,

$$P_{\text{syn}} \approx \frac{2e^4 c^2 B^2}{3m_e^2 c^7},$$

which is so strong that the cooling (energy-loss) time $t_{\text{syn}} \sim \epsilon/P_{\text{syn}} \sim 10^{-13}s$ turns out to be much smaller than the kinematic timescales.

Notice that the aforementioned classical expression for power emission must be appropriately corrected when quantum effects become important. The quantum modification of the synchrotron mechanism is controlled by the parameter $\xi \equiv 3\gamma^2 B \sin \psi$,

$$\xi \equiv \frac{3}{2} \gamma^{-2} B \sin \psi,$$

where $\gamma \equiv \epsilon/mc^2$ is the Lorentz factor of the ultra relativistic electrons, $B \equiv B/B_{cr}$, $B_{cr} = m_e^2 c^3/(\hbar e) \approx 4.4 \times 10^{13}$G is the Schwinger limit for the magnetic induction and $\psi$ is the pitch angle of particles. For particles with $\epsilon \sim 1$PeV, the aforementioned parameter is of order $10^2$ implying that we are deep in the quantum domain. In [Sokolov & Ternov 1968] the authors argue that the total energy emitted by electrons in the ultra quantum case may be approximated by

$$P_q = \frac{2^{8/3} \Gamma (\frac{2}{3})}{9 \xi^{-4/3}} P_{\text{el}},$$

where $\Gamma(z)$ is the Euler Gamma function. Even in the quantum domain, the estimated cooling time scale is still extremely small, and therefore, the quantum synchrotron radiation remains an efficient energy loss mechanism. The power spectrum of "quantum"
synchrotron emission of a single particle is given by (Brainerd 1987)
\[
\frac{dW}{d\omega dt} = \frac{\sqrt{3} e^2 mcB}{2\pi h} \sin \psi F, \quad (16)
\]
where
\[
F_\xi(x) = x \int_{x/(1-\xi)}^{\infty} K_{5/3}(x')dx' + \frac{x^3 \xi^2}{1 - x^\xi} K_{2/3} \left( \frac{x}{1 - x^\xi} \right) \quad (17)
\]
\[
x = \frac{2}{3\gamma^2 B \sin \psi}, \quad (18)
\]
and \(\epsilon_{ph}\) is energy of the synchrotron photon in units of \(mc^2\). The function \(F_\xi(x)\) reduces to the classical expression when the parameter \(\xi\) goes to zero.

In the opposite limit, \(\xi \gg 1\), deviations from the classical expression become highly significant. In fact, "discrete" quantum processes become dominant and the radiation process ceases to be continuous. In this domain of primary interest (to this paper), the standard process of synchrotron self Compton (SSC) mechanism may not be the most effective in determining the very high energy emission of pulsars because SSC requires that the relativistic particles continuously emit synchrotron photons. The ultra relativistic particles, however, will likely lose almost their entire kinetic energy in a single quantum event - the emission of a very energetic photon and as a result the emission is not continuous. Consequently, the SSC, requiring a sea of energetic photon and as a result the emission is not continuous. Consequently, the SSC, requiring a sea of photons (in turn, continuously emitted by the same particle), becomes much less probable.

The next step, therefore, is to investigate how transparent the medium of the Crab nebula is to these ultra-high energy gamma-rays. The principal modes controlling the propagation of these high energy photons will be: 1) interaction with other but softer photons, 2) interaction with nebular matter.

Photon - photon interaction leads to efficient pair creation when the soft photons have frequency of the order of the magnitude. Therefore, this particular part of interaction may not be very important and we neglect it.

The corresponding maximum cross section is approximately (Aharonian 2004)
\[
\sigma_{\gamma\gamma} \approx 0.2\sigma_T. \quad (20)
\]
Equation (19) reveals that the \(\gamma\gamma\) interaction of the \(\sim 0.1\)PeV - 1PeV photons will be highly efficient with very low energy soft photons. From (Hester 2008) it is clear that for photons with \(\nu \sim 10^{11}\)Hz, the luminosity of the Crab nebula is of the order of \(\sim 10^{35}\)erg/s. This in turn means that the number density of these photons,
\[
n_{\gamma\gamma} \approx \frac{L}{4\pi r_n^2 c h\nu} \approx 3 \times \frac{PeV}{\epsilon_{ph}} \frac{cm}{m^3}, \quad (21)
\]
is so small that the lengthscale of the \(\gamma\gamma\) interaction
\[
\lambda_{\gamma\gamma} \approx \frac{1}{\sigma_{\gamma\gamma} n_{\gamma\gamma}} \approx 2.5 \times 10^{24} \frac{\epsilon_{ph}}{PeV} \frac{cm}{m}, \quad (22)
\]
e xceeds the Crab nebula size by several orders of magnitude. Therefore, this particular part of interaction may not be very important and we neglect it.

The ultra high energy photons with \(\sim 0, 6\)PeV might encounter also the \(\nu \sim 3 \times 10^{11}\)Hz cosmic microwave background (CMB) soft photons. The problem of absorption of ultra-high energy photons by CMB photons was considered in detail by Kohri et al. (2012). The authors also plotted dependence of attenuation length on photon’s energy. In our case, the corresponding value is \(\lambda \sim 50\)kpc, which means that the absorption factor, \(f\), is given by
\[
f \approx \exp (-d/\lambda) \simeq 0.96. \quad (23)
\]
Therefore, a very small fraction, only 4% of 0.6PeV photons which potentially could have been reached the earth, will undergo efficient pair creation producing electrons, with energies (Aharonian 2004)
\[
\frac{\epsilon_{ph}}{2} \left( 1 - \sqrt{1 - \frac{m_e^2 c^4}{h\nu \epsilon_{ph}}} \right) \leq \epsilon_e \leq \frac{\epsilon_{ph}}{2} \left( 1 + \sqrt{1 - \frac{m_e^2 c^4}{h\nu \epsilon_{ph}}} \right). \quad (24)
\]
in the following interval 40TeV and 600TeV respectively.

By taking into account that pulsars emit in two relatively narrow channels, one can straightforwardly arrive at an approximate value of the net flux of 600 TeV energy photons
\[
\frac{dN}{dAdt} \approx 2 \alpha c \gamma_{GJ} \left( \frac{R_c}{d} \right)^2, \quad (25)
\]
where \(\alpha\) is a fraction of magnetospheric electrons involved in the acceleration process up to 600 TeV energies and \(d \approx 2\)kp is the distance from the Crab pulsar.
In (Borione et al. 1997) the authors examined $2.4 \times 10^9$ events detected by the Chicago Air Shower Array-Michigan Muon Array (CASA-MIA) experiment to study ultra-high energy ($>100\text{TeV}$) gamma-rays from the Crab pulsar and nebula. It has been shown that an integral flux limit from the Crab nebula is of the order of $1.63 \times 10^{-16} \text{cm}^{-2}\text{s}^{-1}$. After combining this value with Eq. (25) one can show that $\alpha \simeq 4 \times 10^{-7}$.

The derived number is a significant value because it indicates the fraction of particles involved in the generation of ultra-high energies. On the other hand, it is strongly believed that pulsars might contribute to the generation of cosmic rays, (Hooper et al. 2009) and therefore, in studying the population of very high energy cosmic particles, the estimated parameter is significant. It is worth noting that $\alpha$ might be an indirect indicator of the topology of the magnetic field of the pulsar’s magnetosphere and, sooner or later, we are going to study this particular problem as well.

4 Summary

We have explored the consequences of a mechanism of electron’s magneto-centrifugal acceleration and applied it to the Crab pulsar. According to this mechanism, the energy of the rotator (pulsar) is efficiently pumped to the magnetospheric plasma exciting Langmuir waves, which, efficiently Landau damp on the primary electrons accelerating them to enormous energies of the order of $\sim 1\text{PeV}$.

We show that these $\sim 1\text{PeV}$ particles efficiently radiate in the quantum synchrotron regime, producing photons with $\sim 0.6\text{PeV}$. These ultra-high energy gamma rays travel through the nebula to the interstellar medium without much energy loss. In the interstellar region, however, these photons encounter the CMB soft photons, and only small portion of them (4%) by the $\gamma\gamma$ channel efficiently produce very energetic electron-positron pairs.

By considering the observed integral flux of $600 \text{TeV}$ gamma-rays and comparing with the model we have estimated the fraction of magnetospheric particles involved in generation of $\text{PeV}$ energy electrons, $\alpha \simeq 4 \times 10^{-7}$.

Data availability statement

All data generated or analysed during this study are included in this published article.
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