TeV-PeV energy neutrinos and gamma rays from extragalactic milli-second pulsars

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Abstract

The origin of the detected diffuse flux of extragalactic PeV neutrinos during 2010 – 2017 by the Ice Cube Experiment is not clear and various models with sources were proposed for it. In the present work, we try to find theoretically whether pulsars could be one possible source. With our study, we found that the extragalactic millisecond pulsars which are newly born may be one possible source of PeV neutrinos and gamma rays. For the purpose, we took two-step particle acceleration scheme for transferring the rotational energy to the electrons which are accelerated to high energy or boosted up to ~ 0.01 EeV energies or above. The high energy boosted electrons interacted with cold positrons and soft radiation in the acceleration zone might produce Ultra High Energy (UHE) neutrinos and gamma rays. The theoretically derived extragalactic muon neutrino energies are found consistent with the Ice Cube detection.

Keywords: acceleration, pulsars, neutrinos, gamma ray

1. Introduction

The IceCube (RE 10) is a recognized CERN experiment and is a High Energy Neutrino Observatory which is constructed at the Amundsen-Scott South Pole Station, Antarctica and funded by National Science Foundation (NSF). IceCube experiment has thousands of sensors under the Antarctic ice which are distributed over a cubic kilometer. These detect Neutrinos that are massless subatomic particles and act as astronomical messengers to probe the presence of violent astrophysical sources such Gamma Ray Bursts, exploding stars and other cataclysmic phenomena from Neutron stars and Black holes. In 2013 IceCube reported about the discovery of diffuse flux of ultra-high-energy (UHE) cosmogenic neutrinos and the detection has some features that naturally favors possibly extragalactic sources, although the objects is yet to confirm with certainty. Through well-coordinated global multi-messenger astronomical observations of neutrinos along with cosmic rays, electromagnetic radiation across a wide spectrum and also gravitational waves seems a promising contemporary approach to extract crucial information on basic astrophysical issues. The benefit of neutrinos is that they can travel unaffectedly through the densest environment from any astrophysical object and as such may help to probe that can lead an observer back to their sources. Further, the UHE gamma rays are produced along with neutrinos, when they cannot escape their sources owing to absorption in their production region or are absorbed in background radiations. So, with the association of IceCube neutrinos with UHE gamma rays gave an opportunity of identifying the source(s) of astrophysical neutrinos.

Existing literatures and experiment gives a clear indication that cosmic rays/electrons above 10^{17} eV are extra galactic in origin as known galactic objects are not enough energetic to produce cosmic rays/electrons around 10^{17} eV and above. In present work, we have opined that the production of PeV energy neutrinos may be related with power of generated electrons from the extra galactic MSPs. A transition from galactic to extragalactic origin of UHE cosmic rays or electrons is expected to occur at energies around ~ 0.1–1 EeV, and they remain as yet unidentified sources of extragalactic origins. The detection of PeV energy scale neutrinos in the IceCube experiment may unfold a new possibility to correlate them with those probable extragalactic sources. It is thus seemingly advocated that the extragalactic young MSPs might be able to supply enough energy to accelerate electrons to UHEs and thereby producing PeV energy scale neutrinos and gamma rays.

Different searches for astrophysical neutrinos by the IceCube experiment focus on high-energy events that start in the detector volume or that originate in the Northern Hemisphere. During 7.5 years operations (2010-2017), about five PeV neutrinos with energies in the interval [1-10] PeV have been detected [2-4]. These neutrinos might have originated from extragalactic sources of cosmic rays/electrons. These PeV energy neutrino announcements by IceCube had created huge excitement among researchers, and turning their attention towards the search of their astrophysical origin. Usually, all models consider that gamma rays are produced in pp and pγ hadronic interactions that would also generate PeV neutrinos within the source [5-8]. The new- born fast spinning pulsars are considered in this work as probable sources of IceCube neutrinos, and some of the observed gamma rays in several Imaging Atmospheric Cherenkov Telescopes (IACTs). In the framework of an alter- native particle acceleration model, electrons being pumped to UHEs if energy diminution processes remain insignificant during the acceleration of electrons in the magnetosphere of fast spinning pulsars [9]. These electrons with energies beyond 0.01 EeV, might generate PeV neutrinos possibly via; lepton-hadron ($e^- + p \rightarrow n + \nu_e$), and lepton-lepton ($e^- + e^+ \rightarrow \nu_l + \tilde{\nu}_l$; $l = e, \mu, \tau$) reactions. UHE gamma rays are also produced through the more common inverse Compton scattering (ICS) process, ($e^- + \gamma_{\rm low} \rightarrow e^- + \gamma_{\rm high}$).

If the reactions $e^-e^+_{\rm cold}$ and $e^-p_{\rm cold}$ are the source of PeV neutrino events, there should be a supply of UHE electrons with energies all the way over 0.01 EeV. The $e^-\gamma_{\rm low}$ interaction would also require the same energetic electrons for producing PeV gamma rays. Such electrons could indeed be driven successfully by the new-born fast spinning millisecond pulsars (MSPs) through the Landau damping of centrifugally driven Langmuir waves [9]. The pumping of rotational energy of a pulsar into the electric field in the pulsar magnetosphere efficiently supplies the energy for growing Langmuir waves in the bulk electron- positron plasma. The excited Langmuir waves then damp on a faster local electron beam in the vicinity of the light cylinder, accelerating them to larger energies [9-10]. The acceleration mechanism is called the Langmuir-Landau- Centrifugal-Drive (LLCD), has been applied to accelerate electrons/protons in plasmas surrounding the compact objects (pulsars and active galactic nuclei (AGNs)) [11].

The e^- and e^+ population that emanating from the pulsar may be divided into three components: a relativistic $e^-–e^+$ plasma, a tail of the plasma and the remnant of the primary ultra-relativistic electron beam. The set of physical parameters, like the concentration and Lorentz factor, that would characterize of these components are denoted by n_1, γ_1; n_2, γ_2 and n_b, γ_b. In a standard system like a pulsar, a transformation of its rotation energy into energy-driven oscillations in the $e^-–e^+$ plasma away from the star surface is made possible via a parametric two stream instability. The entire plasma around the pulsar is assumed to be composed of so many $e^-–e^+$ plasmas (i.e. multi-stream: each stream with a characteristic n and γ, and also a characteristic phase (φ) [11]). The linear interacting dynamics of two such streams excites the parametric pumping (or two stream instability) of plasma oscillations in the magnetosphere. Eventually the phase difference between the streams emerges as the driver to augment the energy content of the $e^-–e^+$ plasma in the formof Langmuir waves.

In this paper, we mainly focus on the emission of UHE neutrinos contributed by the process of purely leptonic origin, particularly, via $e^-e^+_{\rm cold}$ interaction in extragalactic new-born MSPs. The relevant interaction $e^-\gamma_{\rm low}$, in softer radiation field zones, leading to high-energy gamma ray flux, will be included as a possible counterpart of the detected IceCube PeV neutrinos. The interaction cross section of the process $e^-e^+_{\rm cold}$ reaches to the level of $\sim 10^{-32}$ cm^2[12]. In the pulsar atmosphere, the remnant of the primary electrons/positrons and the electrons/positrons in the plasma streams usually, near the low end of the distribution for which the waves do not satisfy the relative phase (φ_-) restriction (i.e. $\varphi_- > \pi/6$ and a more detail is given in Section II), altogether act as targets for the $e^- + e^+$ interactions. Now, for a young MSP, the electron/positron density close to the light cylinder is $\sim 9 \times 10^{19}(r/R)^2 \sim 10^{18} cm^{-3}$, whereas the $e^{-}-e^{+}$ plasma concentration, that might have not satisfied the relative phase restriction, would vary in the range; $\sim 10^{11} - 10^{14}\ cm^{-3}$. Hence, the density of the targets of the $e^{-}-e^{+}$ interaction might reach up to 10^{18} cm^{-3}.

It should be however mentioned that the $e^{-}p_{\text{cold}}$ interaction scenario seems highly implausible because of very weak scattering of UHE electrons on cold protons. The process has an interaction cross-section at the level of $\sim 10^{-38}$ cm^2 [13], it requires proton densities at the level of $\sim 10^{20}$ cm^{-3} to compete with electrons synchrotron loss. The details about the targets for the $e^{-}e^{+}_{\text{cold}}$ and $e^{-}\gamma_{\text{low}}$ interaction processes will be mentioned later to emphasize the state of the art of this work.

Several models were proposed in recent papers to understand the possible origins of IceCube's detected PeV neutrinos in galactic/extragalactic astrophysical sites. The well-known hadronic interactions by cosmic rays with matter and radiative background might lead to the generation of PeV astrophysical neutrinos. These sources include cores and jets of AGNs [14-15], the prompt and afterglow regions of gamma-ray bursts (GRBS) [16-17], blazars [18], milli-second newly born pulsars/magnetars (assuming pp and pγ inter- actions) [8,19], microquasars [20] and supernovae [21]. Also starburst galaxies [22], large-scale structures and galaxy clusters [23] have also been found in theliterature.

The present work, however, not only involves the lepton-lepton interactions for the generation of PeV neutrinos but also exploits an acceleration mechanism that pumps efficiently the spin down energy of the MSP into the particles' energy. Our main focus is to investigate the aftermath of the acceleration era of relativistic electrons on the relatively low energy positrons and soft radiative fields available in the pulsar environment with a view to producing the PeV neutrinos obtained by IceCube.

The rotational energy of the pulsar is the only source to accelerate the electrons. Furthermore, the pulsar's energy delivering ability is directly linked with its time period of spinning. The most important pair of measurable parameters of pulsars that distinguishes them from each other are the spin period (P) and period derivative ($\dot{P}$). In addition to $P\dot{P}$, the secondary parameters like spin down power ($\dot{E}$) and star's magnetic field ($\boldsymbol{B}$), derived from the timing information $P\dot{P}$ also provided to the ephemeris for all known pulsars (gamma ray and radio pulsars). Diagrams in [24-25], the distribution of $\dot{P}$ as a function of P are shown for known/discovered pulsars along with $\dot{E}$, $\boldsymbol{B}$ and age ($\boldsymbol{\tau}$) contours. The proposed / undiscovered new born MSPs with $\dot{\mathrm{P}} \sim 10^{-12}\mathrm{ss}^{-1}$ in this work are assumed to be evident in the $P\dot{P}$ diagram (region corresponding to $P \sim 1$ ms, $\dot{\mathrm{P}} \sim 10^{-12}\ \mathrm{ss}^{-1}$ and $B \sim 10^{12}$ G [24]. One should however keep in mind that such type of pulsars have not yet been reported from any observation; they are only theoretically predicted [26]. Meanwhile, the Fermi-LAT collaboration has reported GeV gamma ray excess from the Galactic Center region of Milky way [27]. On the other hand, the diffuse TeV gamma ray excess has been observed by H.E.S.S. group [28]. A new population of MSPs could be considered to be potential candidates for explaining the Galactic Center Excess (GCE) according to some recent analyses [29]. Some sort of associations of TeV gamma rays with IceCube's TeV - PeV neutrinos has been suggested in [29]. It is a fact that neutrinos do not loose energy when passing through a radiation/matter unlike the gamma rays. Till date, the physical origins of the GCE remains a subject of debate, one may thus argue that the GC regions of galaxies and also galaxy clusters/star-forming galaxies might be effective locations of activity of the proposed MSPs. We also note that a few of the neutrino events (TeV energies) detected by IceCube, are relatively closer to the GC. The remaining are at other regions of the galaxy, and at extragalactic sites as well [1-2]. Along the way, we assume that this type of high-spinning pulsar is extremely rare in galaxies.

The plan of the paper is the following. A concrete description of the UHE electron production exploiting the LLCD mechanism is presented, in section 2. In section 3, we summarize the adopted particle acceleration model.

2. Electron acceleration via LLCD

We will now provide a basic element of the LLCD mechanism that produce super-energetic electrons over the energy 0.01 EeV, and finally leads to PeV neutrinos and TeV gamma rays reaching at earth as described in section 1.

A compact object with a strong rotation and a strong magnetic field can induce huge electric field (of the order of billion stat volts /cm) near the surface of a fast-spinning MSP. Such a field initially uproots electrons and also protons from the neutron star's surface. The accelerated electrons suffer curvature radiation loss and the emitted photons subsequently undergo e^{-}–e^{+} pair creation until $E_{\gamma} \geq 2m_{e}c^{2}$, and the pairs are further accelerated and emit curvature photons. This process will continue till to a distance in star's magnetosphere from the neutron star surface where the resultant pair plasma density is sufficiently high to screen out the induced electrostatic field [30]. Next, a systematic operation of an astrophysical setting would start working (*e.g.* pulsar or AGN) in the rotating magnetosphere for transferring rotational energy from the pulsar to kinetic energy of electrons. The LLCD act to do the same what one requires here to generate UHE electrons. In highly dense plasmas of concentration in the range 10^{11}–10^{14} cm^{-3} surrounding the fast spinning MSPs, the LLCD undergoes through a two-step process.

In the first step, the Langmuir waves are generated by the bulk electron- positron with the relatively lower Lorentz factor region in the pulsar's magnetosphere. These excited Langmuir waves damp on a local electron beam in the high Lorentz factor end of the plasma distribution, accelerating them to much higher level. This constitutes the last step, and is known as Landau damping which is a consequence of rapid Langmuir collapse. This above combination could supply relativistic electrons with energies up to EeV range in MSPs and AGNs [10,31-32].

From [33], we obtain the characteristic Landau damping rate of energetic plasmas on a relativistic local electron beam

$$\Gamma_{LD} = \frac{n_{GJ}\gamma_{b}\omega_{b}}{n_{p}{\gamma_{p}}^{2.5}} \tag{1}$$

where n_{GJ}, γ_{b} and $\omega_{b} = \sqrt{\left(\frac{4\pi e^{2}n_{GJ}}{m}\right)}$ are Goldreich-Julian density, the Lorentz factor and the plasma frequency of the specific species on which the damping of electrostatic waves settles down. n_{p} and γ_{p} are respectively the plasma number density and its Lorentz factor.

For the effectiveness of the LLCD in fast spinning pulsar's magnetosphere, typically the damping, and the instability growth rates in the bulk plasma, are of the order of 10^4 s^{-1} [11]. On the other hand, the kinematic rate, also called the pulsar's angular rate of rotation (Ω) is close to $\approx 6 \times 10^3$ s^{-1}. Hence, the instability growth and damping rates are faster than the kinematic rate. In the first half of the LLCD, the centrifugal acceleration drives the electrostatic Langmuir waves consuming the central star's rotational energy via parametric two stream instability with a growth rate [11],

$$\Gamma_{GR} = \frac{\sqrt{3}}{2}\left(\frac{\omega_1 \omega_2{}^2}{2}\right)^{1/3} J_\mu(b)^{\frac{2}{3}} \tag{2}$$

where J_μ represents the Bessel's function and b = (2ck/Ω)sinφ_- with $\varphi_- = (\varphi_p - \varphi_e)/2$ (here, φ_p and φ_e denote the initial phases of e^+ and e^-, Ω being the angular velocity of the pulsar, k denotes the wave vector). The several steps analytical treatment of the stream motion [11] in the magnetosphere finally ensures the possibility of the growth of perturbations. In the framework of the perturbation theory the perturbed stream densities involve imaginary exponent. The imaginary exponent can be expressed as a linear combination of the Bessel's functions of different orders through the Bessel identity [11]. The instability growth rate after exploiting some algebra takes an imaginary part through the Bessel's function. In Eq. (2), $\omega_{1,2} = \sqrt{8\pi e^2 n_{1,2} / m\, \gamma_{1,2}{}^3}$, $n_{1,2}$ and $\gamma_{1,2}$ are the relativistic plasma density, the number density and the Lorentz factor respectively of the two species i.e. e^+ and e^-.

We have learned already that the particles of electron-positron plasma have received pulsar's rotational energy. In the cosmic rest frame these particles start to slide along the magnetic field lines experiencing the centrifugal force in a frozen-in condition (radial velocity ~ 0) [34]. The reaction force f_r relative to the laboratory frame pushes the particles towards the boundary of the pulsar's light cylinder. In the vicinity of the light cylinder surface the particles would gain the maximum energy from the pulsar's magnetosphere and is equal to the total work done by f_r

$$W_e \approx n_1 f_r \,\delta r\, \delta V, \tag{3}$$

where $\delta r \approx c/\Gamma$ is the scale distance and δV is the corresponding volume within which pumping occurs [34-35]. The local beam electrons will receive energy by the above work done in the same volume. If ϵ_e is the energy gained by each beam electron, then $W_b \approx n_{GJ}\epsilon_e\delta V$, would therefore give the total energy gained by all the beam electrons available in the volume. The total energy gained by a beam electron has been found by making, $W_b \approx W_e$, as [10, 34]

$$\epsilon_e \approx \frac{n_1 f_r \delta_r}{n_{GJ}} \tag{4}$$

In Eq. (4), we can use, $f_r \approx 2mc\Omega\,(1 - \Omega^2 r^2/c^2)^{-3/2} \equiv 2mc\Omega\xi^{-3}$; ξ is called the time lapse function and is estimated to $\sim 10^{-3}$ [34]. For the young MSP, we take $P \sim 10^{-3}$ s and $B_{lc} \approx B(R/R_{lc})^3$ with $R_{lc} \equiv c/\Omega$. Here, B_{lc} is the magnetic field on the light cylinder zone, R and R_{lc} are radii of the pulsar and its light cylinder. For the two-stream instability, the instability growth and Landau damping rates are large and comparable. By considering $B \approx 10^{12}$ G, the magnetic field near the star's surface, and $\dot{P} \sim 10^{-12}\,ss^{-1}$ and for the combination; $\gamma_1 \approx 1.8 \times 10^5$, $\gamma_2 \approx 8 \times 10^5$, and $\gamma_b \approx 7.5 \times 10^7$, the desired condition i.e. $\Gamma_{GR} \sim \Gamma_{LD} \equiv \Gamma \sim 10^4\,s^{-1}$ can be achieved by the LLCD [10]. In regions close to the light cylinder, the Goldreich-Julian number density $n_{GJ} \equiv (B/Pec)$ is $1.8 \times 10^{12}\,cm^{-3}$. The radius r of an electron from the center of the pulsar (Pulsar's own radius is taken to $R \approx 10^6$ cm) is taken roughly equal to $r \approx 5R$, and for typical magnetospheric parameters of the pulsars under the present study, the Eq. (4) estimates electrons energy close to 0.27 EeV, provided, $f_r \approx 3.4 \times 10^{-4}$ in CGS unit. One of the magnetospheric parameters like the stream density n_1, is taken as $\approx 7.5 \times 10^{14}\,cm^{-3}$. This value for the stream density has been computed using a rough equipartition of energy in the two constituents as, $n_1\gamma_1 \approx n_{GJ}\gamma_b$.

The UHE electrons interact with low-energy/cold positrons beyond the light cylinder zone, the unstable Z boson state may form which then decays into five individual channels with different branching fractions. At Z boson peak, the branching ratio (BR) of the Z boson decay into $\nu_l\tilde{\nu}_l\;(l = e, \mu, \tau)$ together is roughly 1/5. The remaining BR of amount 4/5 accounts for the production of charged lepton pairs $(l = e^{\pm}, \mu^{\pm}, \tau^{\pm})$. The average percentage of UHE electrons energy carried out by the neutrinos via the unstable Z boson state is ~ 20%. Hence, each of the neutrino, irrespective of their flavors could receive ~ 3% of the projectile's energy via the $e^- e^+ \rightarrow \nu_l \tilde{\nu}_l$ reaction channel.

$$E_\nu \approx 0.03\, E_e \approx 1.5(PeV)\ \epsilon_{e,17}[2/(1+z)]. \tag{5}$$

Here, $\epsilon_e = \epsilon_{e,17}(10^{17} eV)$, being the electron energy in the cosmic rest frame and z is the gravitational redshift of the source.

From [36], it was concluded that at the beginning of electron acceleration, the cooling time scale due to ICS is longer than the acceleration time scale which means insignificant loss of electron energy. In the vicinity of the light cylinder ($r \leq R_{lc}$), the rotational energy gain of electrons is strongly limited by the mechanism called 'breakdown of the bead on the wire' (BBW) approximation [37]. Beyond the light cylinder i.e. ($r > R_{lc}$), efficient energy transferring to electrons materializes via Langmuir collapse [11]. The resulting Lorentz factor of the electrons reaches to a maximum value $\approx 10^6$–10^7. The soft photons in nearby regions will attain a maximum energy via ICS by the UHE electrons with average Lorentz factor $\approx 5 \times 10^6$ [36].

$$E_\gamma \approx \frac{\gamma_{max}^2}{10^{10}} \approx 2.5\ PeV \approx 0.025 E_e \approx 1.25(PeV)\epsilon_{e,17}\left[\frac{2}{1+z}\right] \tag{6}$$

A very young MSP with rotational period P ~ 1 ms, could have an associated rotational energy $E_{rot} = (1/2)\ I\Omega^2 \approx 1.6\times10^{52}$ erg, (putting $I \approx 10^{45}$ gcm^2, the star's moment of inertia). Consideration of P ~ 1 ms as the early phase rotational period is appropriate to $E_{rot} \approx 10^{52}$ erg in the present case. We account the star's spin-down in contributing to spin-down luminosity (L_{sd}). The L_{sd} is roughly equal to the electromagnetic luminosity of the MSP (assuming gravitational wave losses by the MSP are unsubstantial). Therefore, the bolometric luminosity (L_b) of the MSP then reads [38]

$$L_b \approx L_{sd} \approx \frac{\mu^2\Omega^4}{c^3} \approx 5 \times 10^{43}\, erg/s \tag{7}$$

where $\mu = BR^3$ is the dipole moment of the star under consideration. Suppose, a fraction η_k is consumed in the acceleration process of electrons close to EeV energies. Electrons with an energy given below, finally impinge upon their respective targets just outside the pulsar's light cylinder.

$$\epsilon_e = \frac{\eta_k L_b}{4\pi \eta_p R_{lc}^2 n_{GJ} c} \tag{8}$$

where η_p accounts the fraction of electrons participated in the acceleration process which is expected to be smaller than 1. We have already found that the Eq. (4) yielded electrons energy $\approx$ 0.27 EeV, for a set of typical values of the parameters involved in the equation. Comparing Eq. (4) with Eq. (8), an estimate of the ratio η_k/η_p in (8), can be known, and it is $\sim$ 60. In the following section, it would be possible to limit the parameter η_k from the comparison between the IceCube estimated and our calculated PeV neutrinos fluxes with equal contribution from all neutrino flavors.

It is noteworthy to mention that the electrons kinetic (flux) luminosity $L_{k,e}$ contains a fraction of the L_{sd} or L_b. It is therefore inevitable that, $L_{k,e} < L_b$, and the ratio of $\frac{L_{k,e}}{L_b} = \eta_k$ known as the loading factor of cosmic ray electrons, has been introduced already in Eq. (8), should be definitely smaller than 1. Again the probability of e^-e^+ and $e^-\gamma$ interactions would alter the efficiency of conversion of the $L_{k,e}$ to generate PeV neutrinos and gamma rays. Thus, one more parameter (ξ_s) is needed to be introduced in order to account the amount of suppression of the UHE electron flux to power UHE neutrinos and gamma rays. If the bolometric luminosity rises, the kinetic luminosity will accordingly modify the energy of emitted electrons, and hence to the neutrino/gamma ray energies [39].

In the pulsar's magnetosphere, the regions far away from the central star where the initial electrostatic field is screened, the electron-positron plasma and soft photons are sufficiently dense with the order of magnitudes ~ 10^{11}–10^{14} cm^{-3} and ~ 10^{19} cm^{-3} [8] respectively. Copious thermal photons emitted from the star are also available there.

In the LLCD model, the e^-–e^+ plasma were assumed to be multi-stream. The plasma can be described by a widespread distribution function containing several streams, each characterized by a Lorentz factor. Langmuir waves generate by two streams when satisfy a phase difference $\varphi_{-} \leq \pi/6$, can only contribute to particle acceleration [10]. Moreover, these waves possess a phase velocity which is asymptotically close to the speed of light. Hence, particles ($e{+}_{\mathrm{cold}}$) in the plasma streams usually near the low end of the distribution and for which the waves do not satisfy the above relative phase restriction (with $\varphi_{-} > \pi/6$), may act as targets for the e^{-}–e^{+}_{cold} interactions. A certain fraction of these particles in multi-stream may also undergo synchrotron losses and supply photons. These nascent photons and the star's ambient radiation field together may act as γ_{low}, and would participate in theICS process with the UHE electrons.

It has been already stated that the parametric pumping of Langmuir waves is a highly efficient process. In the present astrophysical settings the second step i.e. Langmuir collapse is also a rapidly energy transferring process. We will now look upon very briefly about the possible energy loss mechanisms that may impose significant constraints, if any, during the energy transfer stage to electrons [10].

The overall acceleration time-scale is much smaller than the cooling time- scale for a broad range of γs; the instability is indeed very efficient (acceleration/instability time-scale is ~ 0.1 ms, smaller than the Compton cooling time, $t_{cc} \sim \epsilon_e / P_{KN}$ due to the ICS process in the Klein-Nishina regime) [9-10]. Moreover, the cooling time-scale of the ICS process is a continuously increasing (or slow process) function of ϵ_e. The most potential synchrotron loss mechanism does not affect the continuous energy acquiring mode of electrons. The relativistic electrons leaving the pulsar's vacuum gap experience an efficient synchrotron cooling at a very short time scale 10^{-21} s [9]. As soon as the electrons crossing the gap, they radiate their transverse momentum, but in no time they drifting along the field lines, and reaching near the light cylinder zone. This is the space, where the Langmuir waves, always propagating along the field lines, are excited due to the event of wave interaction with particles, thereby readily suppressing the synchrotron cooling. The next possible energy loss process is the curvature radiation; the cooling time-scale of the mechanism in this environment takes much higher values than the overall acceleration time-scale and, hence does not interfere notably with the energy transfer process. The energy density of electrons with energies close to PeV and above exceeds the magnetic energy density by several orders of magnitude. At this situation, electrons follow practically straight line trajectories, thereby excluding the curvature loss from the interference with the wave energy transfer via LLCD.

3. Summary

We have theoretically found a possibility of the generation of PeV neutrinos ever detected through a specific lepton-lepton interaction channel in newly born extragalactic MSPs. A possibility of the generation of PeV gamma rays through the ICS process has also been investigated from the theory. Our conclusions are summarized as follows.

We have reviewed the LLCD mechanism in the context of a MSP for accelerating electrons to the UHE in the magnetosphere. A two-step process of electron acceleration is adopted: (i) generation of electrostatic Langmuir waves from the conversion of star’s rotational energy to the electrostatic energy and (ii) an efficient collapse of Langmuir waves on local beam of electrons leading to their acceleration.

If electrons reach at the level ≥ 0.01 EeV in the young pulsar’s magneto-sphere, they interacting with targets/ambient matter (positrons) and radiation (photons) in the acceleration region just beyond the light cylinder of the MSP, produce PeV neutrinos and gamma rays.

Hadronic scenarios are widely accepted for the production of high-energy neutrinos. Most of the models proposed in earlier studies took pγ and/or pp interactions for the production of UHE neutrinos in different sources. The present study involves the lepton-lepton interactions, occurring near the acceleration region of the young MSPs, generating the UHE astrophysical neutrinos.

Here, we have shown that the leptonic scenario in some extreme astrophysical settings, such as newly born extragalactic MSPs, might have contributed to the PeV neutrino flux observed by the IceCube experiment.

We have derived the associated gamma ray flux from the theory and they are

unlikely to be available on earth due to stronger absorption in regions surrounding their production site, and over their long cosmological distances. A fraction of these PeV gamma rays might be converted into TeV gamma rays over the cosmological distance and would be detected at gamma ray observatories.

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