Efficiency of Centrifugal Mechanism in Producing PeV Neutrinos From Active Galactic Nuclei

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ABSTRACT
A several-step theoretical model is constructed to trace the origin of ultra high energy (UHE) \([1 \sim 2]\text{PeV}\) neutrinos detected, recently, by the IceCube collaboration. Protons in the AGN magnetosphere, experiencing different gravitational centrifugal force, provide free energy for the parametric excitation of Langmuir waves via a generalized two-stream instability. Landau damping of these waves, outside the AGN magnetosphere, can accelerate protons to ultra high energies. The ultimate source for this mechanism, the Langmuir-Landau-Centrifugal-Drive (LLCD), is the gravitational energy of the compact object. The LLCD generated UHE protons provide the essential ingredient in the creation of UHE neutrinos via appropriate hadronic reactions; protons of energy \(10^{17}\text{eV}\) can be generated in the plasmas surrounding AGN with bolometric luminosities of the order of \(10^{43}\text{ergs s}^{-1}\). By estimating the diffusive energy flux of extragalactic neutrinos in the energy interval \([1 \sim 2]\text{PeV}\), we find that an acceptably small fraction 0.003\% of the total bolometric luminosity will suffice to create the observed fluxes of extragalactic ultra-high energy neutrinos.

Subject headings: neutrinos – (ISM:) cosmic rays – galaxies: active – plasmas – magnetohydrodynamics (MHD)

1. Introduction

The recent discovery of the ultra high energy (UHE) extra-solar neutrinos by the Ice Cube collaboration (Aartsen et al. 2013) is particularly interesting. The neutrino trajectories, in contradistinction to those of the UHE charged particles, are unaffected by the galactic magnetic field, and can lead the observer back to the origin of the emanation.

In the Ice Cube announcement, two events - neutrinos of energies \(1.04\text{PeV}\) and \(1.14\text{PeV}\) with a high significance of observations are emphasised. An analysis of the observational data between 2010 and 2013 also shows an event that corresponds to even higher energy of \(2\text{PeV}\) (Aartsen et al. 2014). The IceCube observations are very significant not only for studying the origin of the UHE neutrinos but in general for exploring the astrophysical origin of cosmic rays.

It is usually assumed that the UHE neutrinos are generated via interactions of UHE protons, during which, approximately 4\% of the initial proton energy is imparted to the neutrinos, \(\text{(Murase et al. 2013):}\)

\[ E_\nu \approx 0.04E_p \simeq 2\text{PeV} \epsilon_{p,17} \frac{2}{1 + z}, \]  

(1)
where $\epsilon_{p,17} = \epsilon_p/10^{17}\,\text{eV}$ is the normalized proton energy in the cosmic rest frame and $z$ is the redshift of the corresponding object.

If the proposed hadronic processes were the source of $1-2\,\text{PeV}$ neutrinos, one must demand a supply of protons with energies of the order of $10^{17}\,\text{eV}$ (Murase et al. 2013). Such a population of UHE protons, could, indeed, come from the active galactic nuclei (AGN) (Kim & Kim 2013).

In face, guided by this observational correlation, we have recently proposed a plausible mechanism (Osmanov et al. 2014; Osmanov 2008) and worked out a model for driving protons to ultra high energies in the AGN vicinity.

In the framework of our alternative model the story of UHE charged particles begins with tapping the gravitational energy to excite Langmuir waves in the highly relativistic plasmas present in the rotating magnetospheres of compact objects. The new mechanism, called the Langmuir-Landau-Centrifugal Drive (LLCD), has been described in several papers, and in considerable detail in (Mahajan et al. 2013). Applied successfully to demonstrate extreme particle acceleration in plasmas surrounding the pulsars (Osmanov et al. 2015; Mahajan et al. 2013; Machabeli et al. 2005) and the AGN (Osmanov et al. 2014; Osmanov 2008), the LLCD operates in following successive steps:

1) Differential and time dependent centrifugal force, parametrically, destabilizes Langmuir waves. The pumping of rotational energy into the electric field is extremely efficient in the vicinity of the light cylinder (LC) surface (a hypothetical area, where the linear velocity of rotation exactly equals the speed of light).

2) These growing Langmuir waves, sustained in the bulk plasma (either electron-positron or electron- proton), damp on a faster component of particles, accelerating them further. In the AGN this energy transfer is further boosted by a Langmuir collapse prior to Landau damping.

3) The overall process is most efficient when the rate of transfer from rotational to electrostatic energy (growth rate of instability in the bulk plasma) is comparable to the rate of transfer from electrostatic to kinetic energy (damping rates on the fast particles).

Before we dwell on the LLCD led neutrino energization, let us recall various mechanisms in the literature that are likely to contribute to the observed flux of PeV neutrinos (from all AGN):

1) In Atoyan & Dermer (2001) the authors have assumed that in blazars, protons accelerate with the same power as electrons and are injected with the number spectrum $-2$. Under these circumstances it has been shown that the pion photo production process might lead to generation of very high energy neutrinos. The authors in Mannheim et al. (2001) consider the limits of neutrino background based on the observationally evident intensity of extragalactic gamma-rays. An analysis of the photon spectrum (Cholis & Hooper 2013) predicts AGN neutrinos with energies even higher than detected by the IceCube collaboration. Such a conclusion, however, is model dependent.

2) Two similar studies, investigating the production of UHE neutrinos, are noteworthy: a) Stecker et al. (2013), the high energy neutrinos arise from AGN cores where particles are accelerated by shocks, and b) in Kalashev et al. (2015), the process of photopion production in the Shakura-Sunyaev accretion disks is invoked to explain the observed Ice Cube neutrino flux.

Our work, however, exploits a totally different process- PeV neutrinos are created by the centrifugally accelerated protons. Instead of focusing on the accretion disk as a location where the neutrinos might arise, we estimate the diffusive effect of all AGNs and show that the average fraction 0.003% of the bolometric luminosity of these objects is enough to produce the observed flux of PeV neutrinos. To the best of our knowledge, this work constitutes the first attempt of this kind. The present mechanism does not contradict aforementioned mechanisms of acceleration, but instead is an alternative process, which might take place in rotating magnetospheres.

This paper is organised as follows: in section 2 we review the LLCD mechanism, in section 3 we consider the energies of neutrinos and the corresponding flux and in section 4, we summarise our findings and results.

2. Review of LLCD

We will now summarise aspects of the LLCD that are most relevant to the creation of UHE protons, and, consequently, the UHE neutrinos.
Acceleration of protons strongly depends on the angular velocity of the black holes

$$\Omega \approx \frac{ac^3}{GM} \approx 10^{-3} \frac{a}{M_\odot} \text{rad/s},$$

(2)

where \(c\) is the speed of light, \(M_\odot \equiv M/(10^8 M_\odot)\) is the normalized mass of the supermassive black hole, \(G \approx 6.67 \times 10^{-8} \text{dyne-cm}^2 \text{g}^{-2}\) is the gravitational constant and \(0 < a \leq 1\) is a dimensionless parameter characterizing the spinning rate of the black hole.

In the AGN (pulsar) magnetospheres, the magnetic field is strong enough to justify the so-called frozen-in assumption; the particles, essentially, follow the co-rotating field lines. The magnetic field in the AGN magnetosphere is estimated as (Osmanov 2008)

$$B \approx 87 \times \left( \frac{L}{10^{43} \text{erg s}^{-1}} \right)^{1/2} \times \frac{R_{lc}}{r} G,$$

(3)

where \(L\) is the luminosity, \(R_{lc} \equiv c/\Omega\) is the light cylinder radius and \(r\) is the radial distance from the supermassive black hole. One can straightforwardly check that the gyroradii of electrons and protons, characterized with the Lorentz factors of the order of \(10^4 - 6\), are much less than the kinematic lengthscale, \(R_{lc}\). Therefore, the frozen-in condition will be maintained almost during the whole course of motion.

But it turns out that the energies corresponding to the centrifugal acceleration, are not high enough to account for the highly energetic cosmic ray protons. In Osmanov et al. (2014) and Osmanov (2008) we discussed two major mechanisms that limit the acceleration process: the inverse Compton scattering, and the so-called "breakdown of the bead on the wire approximation" (Rieger & Mannheim 2000). It has been shown that the latter is much more efficient and limits the maximum attainable Lorentz factor to

$$\gamma_{BBW} \approx \frac{1}{e} \left( \frac{e^2 L}{2m} \right)^{1/3} \approx 3 \times 10^3 \left( \frac{m_p}{m} \times \frac{L}{10^{43} \text{erg s}^{-1}} \right)^{1/3},$$

(4)

where \(e(m)\) is the electron charge (mass); the latter is normalized on the proton mass, \(m_p\). The \(\gamma_{BBW}\) is not high enough for the cosmic ray energy range that we seek to explain. One obtains a similar result for electrons.

Direct centrifugal acceleration, therefore, cannot boost particle energies up to the very-high energy domain. The relativistic centrifugal effects, however, do play an indirect role in additional particle acceleration: it is this very time-dependent, differential centrifugal acceleration that, first, transfers the rotational energy into Langmuir waves via a parametric two stream instability with a growth rate (Osmanov et al. 2014)

$$\Gamma = \frac{3}{2} \left( \frac{\omega_p \omega_e^2}{e_p} \right)^{1/2} J_b(b)^{2},$$

(5)

where \(J_{\mu}(x)\) denotes the Bessel function, \(b = \omega_e/\Omega\), \(\omega_{e,p} = \sqrt{4\pi e^2 n_{e,p}/m_{e,p}^2 \gamma_{e,p}^3}\) and \(\gamma_{e,p}\) are, respectively, the relativistic plasma frequency, the number density and the Lorentz factor of the corresponding specie (electrons or protons). By considering the parameters \(L \sim 10^{43} \text{erg s}^{-1}, \gamma_e \sim \gamma_{BBW,e}, \gamma_p \sim 10^2\), after taking into account the equipartition distribution of energy among protons with different energies, one can show that the instability time-scale is less than the kinematic time-scale, \(R_{lc}/c\), by three orders of magnitude. We assume that energy distribution of particles is continuous and thus, apart from the ultra-high energies, there are relativistic protons with relatively low Lorentz factors. As we have shown, the parametric instability for particles with \(\gamma_p \sim 100\) is extremely high and only this particular class of protons can very efficiently contributes in the mentioned process. It is worth noting that despite the fact that Eq. (4) is derived in the linear approximation, the driving force - the centrifugal force - might be very large and consequently the energy pumped into the waves is huge even in the linear regime. On the other hand, as it has been discussed in detail by Osmanov et al. (2014) and Mahajan et al. (2013) the parametrically unstable Langmuir modes have superluminal phase velocities and since there are no particles with such speeds, the electrostatic waves will not Landau damp increasing their energy until the Langmuir collapse.

In the second stage, the growing energy of
the Langmuir waves is efficiently extracted by particles in a two stage process: the wave energy is spatially concentrated through what is called the Langmuir Collapse (Zakharov 1972, Artsimovich & Sagdeev 1979), and then it Landau damps on the faster particles; the collapse does not develop in the inner magnetosphere \((r < R_{lc})\), where the magnetic field is dominant (Osmanov et al. 2014; Osmanov 2008). Outside this zone, the energy of the electrostatic field evolves as (Artsimovich & Sagdeev 1979)

\[
\frac{|E|^2}{8\pi} \approx \frac{|E_0|^2}{8\pi} \left( \frac{t_0}{t_0 - t} \right)^2
\]

where \(E_0\) is the initial value of the electric field and \(t_0\) is the time of ”complete” collapse. The energy density of the electric field grows explosive, pulling protons from the caverns, and then efficiently transferring energy from the electrostatic waves to the particles via Landau damping. As a result, the protons are driven to UHE (Osmanov et al. 2014),

\[
\epsilon_p(eV) \approx \frac{ne^2}{4\pi^2\lambda_D^3} \Delta r^5 \approx 1.14 \times 10^{17} \times \left( \frac{g}{10^{-3}} \right)^3 M_8^{-5/2} L_{43}^{5/2},
\]

where \(\Delta r \approx R_{ic}/(2\gamma_p)\) is the width of a narrow region close to the LC where the process of acceleration takes place, \(\lambda_D\) is the Debye Length, and \(n = \frac{L}{4\pi\eta m_p c^2 v R_{ic}^2} \approx 6.3 \times 10^6 \times L_{43} \times R_{ic, c}^{-2} \text{ cm}^{-3}\)

\[
(8)
\]

is the approximate value of the proton number density outside of the LC, \(L_{43} \equiv L/(10^{43} \text{ ergs s}^{-1})\), \(R_{ic, c} \approx 3 M_8 \times 10^{14} \text{ cm}\) is the light cylinder radius, and \(g\) is the initial dimensionless density perturbation. This estimate is done for \(\gamma_p = 100\). In the current paper we have assumed that only 10 per cent of the rest energy of accretion matter \((\eta = 0.1)\) transforms to emission.

It is clear that during the process of acceleration particles might potentially lose energy and the corresponding scenario has to be examined as well. This particular problem has been studied by Osmanov et al. (2014) and for detailed analysis a reader is referred to it. Here we only briefly outline the results of the mentioned work. The synchrotron mechanism of energy losses is so efficient that soon after the beginning of motion the protons lose their transverse momentum, transit to the ground Landau level and the synchrotron process does not affect dynamics any more. For the inverse Compton mechanism it can be shown that the timescale of acceleration behaves linearly with the gained energy and consequently cannot compete with the acceleration timescale, which is a continuously decreasing function of \(\epsilon_p\). The similar result is valid for the curvature radiation, which as it has been estimated in (Osmanov et al. 2014) can be significant only for energies exceeding \(10^{17} \text{ eV}\) by many orders of magnitude.

### 3. Neutrino energies and the flux

In this section we address the significant questions concerning the energies of neutrinos and discuss the produced integral flux by taking into account AGNs having appropriate luminosities.

From Eq. (1), we obtain

\[
\epsilon_{p,17} \approx \frac{1}{4} \times (1 + z) \times \frac{E_\nu}{P_eV}.
\]

Therefore, for \(z_{max} = 6\), one finds that neutrinos in the energy interval \([1 - 2] \text{ PeV}\) will correspond to proton energies in the range \(\epsilon_{p,17} \approx 0.22 - 0.47\). One can further infer from Eq. (4) that if the bolometric luminosity of AGN were in the range \(L_{min} \approx 5.45 \times 10^{42} \text{ ergs s}^{-1} - L_{max} \approx 1.57 \times 10^{43} \text{ ergs s}^{-1}\), protons of required energy could be created via LLCD. In Fig. \(\text{A4}\) we show the behaviour of energies of neutrinos on AGN luminosities normalised by \(10^{43}\text{ ergs s}^{-1}\). The corresponding set of parameters is: \(\gamma_p = 100\), \(g = 0.001\) and \(M_8 = 1\). As it is clear from the plot \(E_\nu (eV)\) is a continuously increasing function of the AGN luminosity, which is a natural result, because more luminous AGNs produce more energetic neutrinos.

Since all AGNs are supposed to be rotating supermassive black holes, one can make a case that the observed UHE neutrino fluxes could, at least partially, originate in their vicinity. IceCube collaboration has announced that the neutrino flux in the energy interval \(100 \text{ TeV} - 1 \text{ PeV}\) is of the order of \(10^{-8}\text{GeV cm}^{-2}\text{s}^{-1}\text{sr}^{-1}\) (Aartsen et al. 2014). Can the proposed LLCD mechanism lead to such neutrino fluxes? And if yes, what is the fraction
of the bolometric luminosity ($\mu$) that goes to PeV neutrinos?

To answer these questions, let us estimate the neutrino flux coming out of our theory. Since the cosmic ray kinetic luminosity, $L_{CR}$ (the total kinetic energy of protons "emitted" by the AGN per second), cannot exceed the bolometric luminosity of AGN, the flux provided by this source takes the form [Weinberg 2008]

$$ F_0(L) = \frac{\chi LR(t_1)^2}{4\pi R(t_0)^2 r_1^3}, $$

(10)

$R$ denotes the scale factor in the Robertson-Walker metric, $t_1$ is time when the cosmic rays were emitted from the source and $t_0$ is time when the cosmic rays reached a detector, $r_1$ is the radial distance of a source at the time $t_1$ and $\chi \equiv L_{CR}/L < 1$. If $\phi(t_1, L)$ measures the number of AGNs (per unit volume/ per unit luminosity), the actual flux of cosmic rays for the luminosity interval $[L; L + dL]$ and the radial distance interval $[r_1; r_1 + dr_1]$ is given by [Weinberg 2008]

$$ dF = F_0(L) dN = 4\pi F_0(L) R(t_1)^2 r_1^2 \phi(t_1, L) |dt_1| \frac{dL}{L}, $$

(11)

where $dN$ is the number of AGN for the aforementioned intervals and $L$ is the exponential luminosity cut-off.

By taking into account the relations $R(t_0)/R(t_1) = (1 + z)^{3\alpha}$, $|dt_1| = cH_0^{-1} (1 + z)^{-5/2} dz$, where $H_0 = 67.8 \text{km/s/Mpc}$ is the Hubble constant [Ade et al. 2014], and $z$ is the redshift of the object (we have used the value $q_0 = 1/2$ [Weinberg 2008]) Eq. (11) leads to the following cosmic ray flux

$$ F = \frac{2}{5H_0L} \left[ 1 - (1 + z_{\text{max}})^{-5/2} \right] \times $$

$$ \int_{L_{\text{min}}}^{L_{\text{max}}} F_0(L) \phi(L) dL, $$

(12)

$L_{\text{min}}$ ( $L_{\text{max}}$) denotes minimum (maximum) values of AGN luminosities, and $z_{\text{max}}$ is the redshift of the most distant AGN. To our knowledge there is one at a redshift in excess of 5. This is the object described in Barger et al. (2002) with $z = 5.186$, in the Chandra Deep-Field. For the current work, we will simply use $z_{\text{max}} = 6$. To estimate the above integral, one needs the luminosity function, $\phi(L)$, describing the distribution of galaxies in general, and AGN in particular. Observationally, the best fit to the luminosity function has the form

$$ \phi(L) = \phi_0 \left( \frac{L}{L^*} \right)^{\alpha} e^{- L/L^*}, $$

(13)

where $\phi_0 = 0.012 h^3 \text{Mpc}^{-3}$, $\alpha = -1.25$ defines the slope of the power law and $L^* = 1.32 \times 10^{44} \text{erg s}^{-1}$ [Longair 2011].

With this luminosity function, the neutrino diffusive flux comes out to be

$$ F_{\nu}^{\text{theory}} = \frac{2\mu c \phi_0 L^*}{5H_0} \left[ 1 - (1 + z_{\text{max}})^{-5/2} \right] \times $$

$$ \times \left[ \Gamma \left( \alpha + 2, \frac{L_{\text{min}}}{L^*} \right) - \Gamma \left( \alpha + 2, \frac{L_{\text{max}}}{L^*} \right) \right], $$

(14)

where $\Gamma(t, x)$ is the incomplete Gamma function.

From observations, the best power law fit for the neutrino flux may be expressed as [Aartsen et al. 2014]

$$ f(E_{\nu}) \equiv \frac{dN_{\nu}}{dE_{\nu}} \approx $$

$$ \approx 1.5 \times 10^{-8} \times \frac{E_{\nu}}{0.1 \text{PeV}}^{-0.3} \text{GeV cm}^{-2} \text{s}^{-1} \text{sr}^{-1}. $$

(15)

The number of neutrinos carrying energy in the interval $E_{\nu}; E_{\nu} + dE_{\nu}$ is $dN_{\nu} = E_{\nu}^{-1} f(E_{\nu}) dE_{\nu}$; therefore, the total energy flux of neutrinos in the energy interval $[1 - 2] \text{PeV}$ may be written as

$$ F_{\nu}^{\text{obs}} = 4\pi \int_1^2 E_{\nu}^{-1} f(E_{\nu}) dE_{\nu} \approx $$

$$ \approx 9.47 \times 10^{-11} \text{ergs s}^{-1} \text{cm}^{-2}, $$

(16)

where where the factor $4\pi$ takes into account the total solid angle.

Comparing equations (14) and (16), we may conclude that the theoretical predictions for the PeV neutrino flux will be consistent with observations if a rather small fraction ($\mu \approx 3.08\times 10^{-5}$) of the bolometric luminosity were converted to power UHE neutrinos.

### 4. Summary

1. We have presented, here, a theoretical pathway for generating high energy neutrinos in the range $[1 - 2] \text{PeV}$. These neutrinos are produced in hadronic reactions, in particular, by very energetic protons.
2. The first step in the theory, therefore, was to find an astrophysical setting where ultra energy protons are produced. Such a setting was recently explored: it was shown that in the rotating magnetospheres of AGN, UHE protons (\(10^{17}\) eV) could, indeed, be created through LLCD-a two step process that converts the free energy in differential rotation, first to the electrostatic energy in Langmuir waves, and then to particle energy through landau damping of Langmuir waves (Osmanov et al. 2014).

3. Protons with this enormous energy could, then, create ultra high energy neutrinos, recently observed by the IceCube collaboration. By comparison of theoretically derived expression of diffusive energy flux and the observed energy flux for the range \([1−2]\) PeV we have estimated the value of \(\mu \approx 3.08 \times 10^{-5}\) indicating that only a tiny fraction of the total bolometric luminosity is enough to explain the neutrino flux.

This work is a first attempt of this kind, where we considered the role of centrifugal mechanism of acceleration in generation of cosmic protons with energies enough to produce the PeV neutrinos and estimated the average fraction of the total luminosity of AGNs that is responsible for producing the PeV neutrinos.

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Fig. 1.— Dependence of energies of the produced neutrinos on the AGN luminosity normalised by $10^{43}\text{ergs s}^{-1}$. The set of parameters is: $\gamma_p = 100$, $g = 0.001$ and $M_8 = 1$. 