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High energy neutrino production in the core region of radio galaxies due to particle acceleration by magnetic reconnection

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Detection of astrophysical high energy (HE) neutrinos in the range of TeV- PeV energies by IceCube observatory has opened new era in high energy astrophysics. Neutrinos with energies $\sim$ PeV imply that they are originated from a source where cosmic rays (CRs) can be accelerated up to $\sim 10^{17}$eV. Recently it has been shown that the observed TeV gamma-rays from radio galaxies may have a hadronic origin and in such a case this may lead to neutrino production. In this work we show that HE protons accelerated by magnetic reconnection in the core region of radio galaxies may produce HE neutrinos via decays of charged pions produced by photo-meson process. We have also calculated the diffuse intensity function for the HE neutrinos which can explain the detected IceCube data.

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1. Introduction

Detection of astrophysical high energy (HE) neutrinos in the range of energies from TeV- a few PeV by IceCube observatory ([1]) has opened new season in high energy astrophysics. Neutrino observations may provide us an unique information to investigate better their origins and could result in finding out of new types of astrophysical sources. The inherent isotropic nature of detected neutrino flux is compatible with a suggested extragalactic origin supported by diffuse high energy γ-ray data. The high energy neutrinos with energies $\sim$ PeV infer that they are originated from a source where cosmic rays (CRs) can be accelerated up to $\sim 10^{17}$eV.

One of the main production mechanisms of the HE neutrinos in the energies TeV-PeV, is the decays of charged pions created in the pp or $p\gamma$ collisions in a variety of astrophysical sources which were considered preferred to the IceCube observation, including active galactic nuclei (AGNs) and gamma-ray bursts (GRBs) ([13]). However, all models are rather ambiguous due to lack of real measurement of astrophysical neutrino flux.

The AGNs as potential extragalactic astrophysical sources to construct the high energy neutrinos via hadronic mechanisms has been of interest since more tan three decades ago are able to accelerate and propagate CRs and also may have emission in GeV-TeV γ-rays. It has been shown that observed Tev γ-rays from low luminosity AGNs (LLAGNs) may have hadronic origins (e. g., [8, 9]) that their results increase the expectation of neutrino emission from these sources.

In this work, we consider magnetic reconnection acceleration model that may occur in the vicinity of BHs that was explored first in the framework of microquasars by [3] (hereafter GL05) and then extended to AGNs by [4] (hereafter GPK10) in which particles can be accelerated in the surrounds of the BH by the magnetic power extracted from events of fast magnetic reconnection occurring between the magnetosphere of the BH and the lines rising from the inner accretion disk.

More recently, [6] (henceforth KGS14) revisited this model exploring different mechanisms of fast magnetic reconnection and extending the study to include also the gamma-ray emission of a much larger sample containing over two hundred sources. They confirmed the earlier trend found by GL05 and GPK10, verifying that there is a correlation between the fast magnetic reconnection power and the black hole (BH) mass spanning 10^{10} orders of magnitude that could explain both the observed radio ([4], hereafter GPK10) and gamma-ray emissions of nuclear outbursts from microquasars and Low-luminosity AGNs, which is also in consistency with the so called fundamental plane.

This model has been applied for galactic sources Cygnus X-1 and Cygnus X-3 ([7]) and extragalactic sources, Cen A, NGC 1275, M87 and IC310 ([8]) to investigate the CR acceleration and emission in the core region of these objects. Their results illustrate that hadronic mechanisms (pp and $p\gamma$) are the main radiative processes to produce the observed γ-rays.

Our aim here is to try to calculate the spectrum of escaping neutrinos and estimate the diffuse neutrino intensity then compare to IceCube data in the context of LLAGNs applying the same acceleration model above.

2. Description of the model

We consider here that the core of LLAGNs, i.e., in the surrounds of the BH near the basis of the jet launching can be acceleration region for the CRs where magnetic reconnection may occur. Assuming that the inner region of the accretion disk/corona system alternates between two states which are controlled by changes in the global magnetic field. Right before a fast magnetic reconnection event, we assume that the system is in a state that possibly characterizes the transition from the hard to the soft state, and adopt a magnetized accretion disk with a corona around the BH. We adopt the simplest possible configuration by considering a magnetized standard geometrically thin and optically thick accretion disk around the BH. The accretion disk drags the magnetic field lines and the magnetosphere can be constructed around the central BH.

The magnetic field intensity in the inner region of the accretion disk can be determine by the conservation of momentum flux between the magnetic pressure of the BH magnetosphere and the accretion flux. The presence of embedded turbulence in the nearly collisional MHD coronal flow of the core region of the AGNs can make reconnection very fast (e.g., [10]).

The physical quantities of magnetic reconnection model such as magnetic field (B), coronal number density (n_c), released magnetic reconnection power by turbulent driven fast reconnection (W), disc temperature (T_d) and the thickness of reconnection layer in the magnetic discontinuity region (ΔR_X) has been derived in KGS15 and applied here.

In the magnetic reconnection current sheet where two converging magnetic flux tubes moving to each other with a velocity V_R, trapped particles there bounce back and forth due to head-on collisions with magnetic fluctuations in the current sheet, their energy after a round trip increases by $< \Delta E/E >\sim 8V_R/3c$, which implies a first-order Fermi process. The energy of particles increases exponentially after several round trips. This mechanism proposed by GL05 which is similar to the shock acceleration where particles confined between the upstream and downstream flows undergo a first-order Fermi acceleration. It should be noted that in the $fast$ magnetic reconnection context, V_R is of the order of the local Alfvén speed V_A, at the surroundings of relativistic sources, $V_R \simeq v_A \simeq c$ and thus the mechanism can be rather efficient.

Recently the particle acceleration rate within the magnetic discontinuity under fast magnetic reconnection driven by turbulence has been calculated by [7] and we used their expression in this work. The accelerated proton in the core region of LLAGNs may have Hadronic interactions (see next section) to produce E neutrinos.

3. Hadronic interactions

It has been demonstrated that core region of LLAGNs is able to accelerate up the relativistic protons up to a few 10^{17}eV ([8]), which implies that these sources could be powerful CR accelerators through the magnetic reconnection mechanism which is a first order Fermi process like (GL05). Based on model proposed by KGS14 and also SGK14 for radiogalaxies, here we show that the synchrotron, $p\gamma$ and pp interactions may cool the protons in the region surrounded by BH (Figure 1) in LLAGNs.

The high energy hadronic interactions including pp and $p\gamma$ lead to the production of HE γ-rays and HE neutrinos via decays of neutral and charged pions respectively. The spectrum energy distribution of HE γ-rays due to these hadronic interactions has been investigated in the framework of radiogalaxies ([8]) and here we study the neutrino emission from nuclear region of radiogalaxies.

Table 1: Model parameters for LLAGNs ($L = 20R_S$).

	Parameters	Model 1	Model 2	Model 3
M_{BH}	BH mass ($M_\odot$)	10^7	10^8	10^9
B	Magnetic field (G)	2.8×10^4	8874	2806
W	Magnetic reconnection power (erg/s)	2.4×10^{42}	2.4×10^{43}	2.4×10^{44}
ΔR_X	Width of the current sheet (cm)	7.2×10^{12}	7.2×10^{13}	7.2×10^{14}
n_c	Coronal particle number density (cm^{-3})	3.6×10^{10}	3.6×10^9	3.6×10^8
T_d	Temperature of the disk (K)	1.2×10^8	2.25×10^8	4×10^8
R_x	Inner radius of disk (cm)	1.7×10^{13}	1.7×10^{14}	1.7×10^{15}
L_X	Extension of the reconnection region (cm)	3×10^{13}	3×10^{14}	3×10^{15}
L	Extension of the corona (cm)	6×10^{13}	6×10^{14}	6×10^{15}
V	Volume of emission region (cm^3)	6×10^{41}	6×10^{44}	6×10^{47}
p	Injection spectral index	1.9	1.7	2.2
E_{max}	Maximum energy for protons (eV)	7×10^{17}	10^{17}	6×10^{16}

3.1 *pp* collisions

The charged pions created through inelastic collisions of the relativistic protons with nuclei of the corona that surrounds the accretion disk by means of channel

$$p + p \to n_1(\pi^+ + \pi^-) + n_2\pi^0 + p + p \tag{3.1}$$

where n_1, n_2 are multiplicities, $\pi^0 \to \gamma + \gamma$, carrying 33% of accelerated proton's energy and $\pi^\pm$ decay and produce the neutrinos. The pp cooling rate is almost independent of the proton energy and given by

$$t_{pp}^{-1} = n_i c \sigma_{pp} k_{pp}, \tag{3.2}$$

where k_{pp} is the total inelasticity of the process of value ~ 0.5. The corresponding cross section for inelastic pp interactions σ_{pp} can be approximately by

$$\sigma_{pp}(E_p) = \left(34.3 + 1.88L + 0.25L^2\right) \left[1 - \left(\frac{E_{th}}{E_p}\right)^4\right]^2 \text{mb}, \tag{3.3}$$

where mb stands for milli-barn, $L = \ln\left(\frac{E_p}{1TeV}\right)$, and the proton threshold kinetic energy for neutral pion (π^0) production is $E_{th} = 2m_\pi c^2(1 + \frac{m_\pi}{4m_p}) \approx 280$ MeV, where $m_\pi c^2 = 134.97$ MeV is the rest energy of π^0. This particle decays in two photons with a probability of 98.8%.

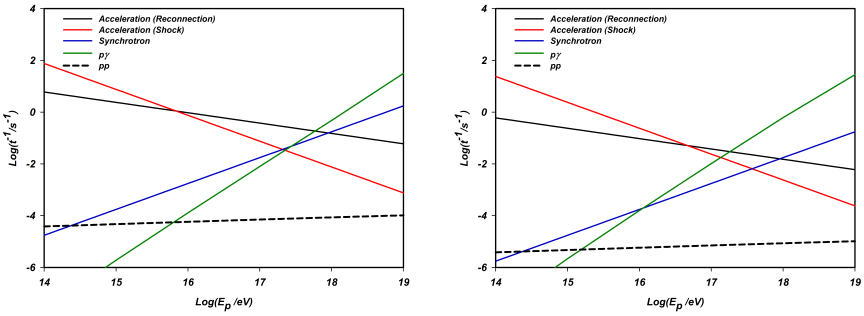
3.2 $p\gamma$ interactions

The photomeson ($p\gamma$) production takes place for photon energies greater than $E_{th} \approx 145$MeV. Pions are also obtained from the $p\gamma$ interaction near the threshold via the channels

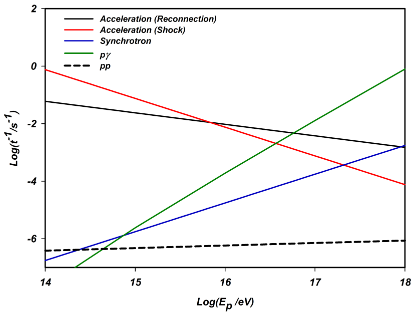
$$p + \gamma \to p + \pi^0, \tag{3.4}$$

which $\pi^0 \to \gamma + \gamma$, carrying 20% of accelerated proton's energy and

$$p + \gamma \to p + \pi^+ + \pi^-. \tag{3.5}$$



(a) *Model* 1 (b) *Model* 2



(c) *Model* 3

Figure 1: Acceleration and cooling rates for the protons in LLAGNs with $L = 20R_S$. (a) Model 1 with central BH mass of $10^7 M_\odot$, (b) Model 2 with central BH mass of $10^8 M_\odot$ and (c) Model 3 with central BH mass of $10^9 M_\odot$.

The cooling rate for this mechanism in an isotropic photon field with density $n_{ph}(E_{ph})$ can be calculated by

$$t^{-1}_{p\gamma}(E_p) = \frac{c}{2\gamma_p^2}\int_{\frac{E^{(\pi)}_{th}}{2\gamma_p}}^{\infty} dE_{ph}\frac{n_{ph}(E_{ph})}{E^2_{ph}} \times \int_{E^{(\pi)}_{th}}^{2E_{ph}\gamma_p} d\varepsilon_r \sigma^{(\pi)}_{p\gamma}(\varepsilon_r)K^{(\pi)}_{p\gamma}(\varepsilon_r)\varepsilon_r, \tag{3.6}$$

where in our model the appropriate photons come from the synchrotron radiation ($n_{ph}(E_{ph}) = n_{synch}(\varepsilon)$) and $\gamma_p = \frac{E_p}{m_e c^2}$, ε_r is the photon energy in the rest frame of the proton and $K^{(\pi)}_{p\gamma}$ is the inelasticity of the interaction. [2] proposed a simplified approach to calculate the cross-section and the inelasticity which are given by

$$\sigma_{p\gamma}(\varepsilon_r) \approx \begin{cases} 340\ \mu barn\ \ 300\text{MeV} \le \varepsilon_r \le 500\text{MeV} \\ 120\ \mu barn\ \ \ \varepsilon_r > 500\text{MeV}, \end{cases} \tag{3.7}$$

and

$$K_{p\gamma}(\varepsilon_r) \approx \begin{cases} 0.2\ \ \ 300\text{MeV} \le \varepsilon_r \le 500\text{MeV} \\ 0.6\ \ \ \varepsilon_r > 500\text{MeV}. \end{cases} \tag{3.8}$$

4. Neutrino emission and diffuse intensity

To calculate the neutrino emission from nuclear region of a radiogalaxy following the model adopted and described in Section 2, we assume that the core region of these sources carries a population of accelerated protons (which are accelerated by magnetic reconnection), whose maximum energy can be calculated by the balance of acceleration and the energy loss rates. Figure 1 shows the acceleration and cooling rates for the protons in the core region of LLAGNs with different SMBH masses employing the set of parameters listed in Table 1. From these figures we can find the maximum energy that the protons can attain in this acceleration process (see Table 1). We also calculated the acceleration time for shock acceleration there to compare with the reconnection mechanism and it is found that maximum energy gained by magnetic reconnection is higher than shock mechanism (see Figure 1). It should be remarkable that protons with this energies still have Larmor radius smaller than ΔR_X, so thickness of current sheet is large enough to satisfy the Hillas criterion.

The luminosity of accelerated relativistic particles in the inner region of accretion disk, is parametrized by a power law distribution in energy which is given by ([7]):

$$L(E_p) = \int_V d^3r \int_{E_{min}}^{E_{max}} dE\ E\ Q(E_p) \tag{4.1}$$

where the isotropic injection function (in units of erg^{-1}cm^{-3}s^{-1}) is given by (see e.g. KGV14):

$$Q(E_p) = Q_0 E_p^{-\alpha} exp[-E_p/E_{max}] \tag{4.2}$$

with $\alpha > 0$ and E_{max} is the cut-off energy. The normalization constant Q_0 is calculated from the total power injected in protons when $L(E_p)$ is equal to the fraction of the magnetic reconnection power that accelerates the protons (see [7]).

The produced neutrinos can escape from the emission region without any absorption and their spectrum is given by([12, 9]):

$$E_\nu L_\nu(E_\nu) \simeq (0.5 t_{pp}^{-1} + \frac{3}{8} t_{p\gamma}^{-1}) \frac{L_X}{c} L(E_p), \tag{4.3}$$

where $E_\nu = 0.05 E_p$, however Figure 1 demonstrates that the $p\gamma$ emission cools the protons faster than pp collisions, so the dominant hadronic process in our model is the $p\gamma$ emission and we expect this mechanism is the dominant channel to produce the neutrinos, so in our model the first term of eq. 4.3 can be neglected.

The maximum energy of produced neutrinos can be calculated by $E_{\nu,max} = 0.05 E_{p,max}$, which in the LLAGNs with $M_{BH} = 10^7 M_\odot$ we found that neutrinos originated from nuclear region can gain energies $\sim 3 \times 10^{16}$eV and in radiogalxies with $M_{BH} = 10^8 M_\odot$, neutrinos may have maximum energies $\sim 5 \times 10^{15}$eV, while neutrinos can have energies $\sim 2 \times 10^{15}$eV in the vicinity of LLAGNs with $M_{BH} = 10^9 M_\odot$.

The observed diffuse neutrino intensity from extragalactic astrophysical objects would have contributions from different redshifts which is given by ([11])

$$\Phi_\nu = \frac{c}{4\pi H_0} \int_0^{z_{max}} dz \frac{1}{\sqrt{(1+z)^3 \Omega_m + \Omega_\Lambda}} \times \int_{L_{min}}^{L_{max}} dL_\gamma\ \rho_\gamma(L_\gamma, z) \frac{L_\nu(E_\nu)}{E_\nu}, \tag{4.4}$$

where $\rho_\gamma(L_\gamma, z)$ is the γ-ray luminosity function (GLF) of the core in radiogalaxies defined as the number density of radiogalaxies per unit comoving volume per unit logarithmic luminosity which is assumed in the redshifts from $z = 0$ to $z = z_{max}$ that z_{max} is the maximum value of the

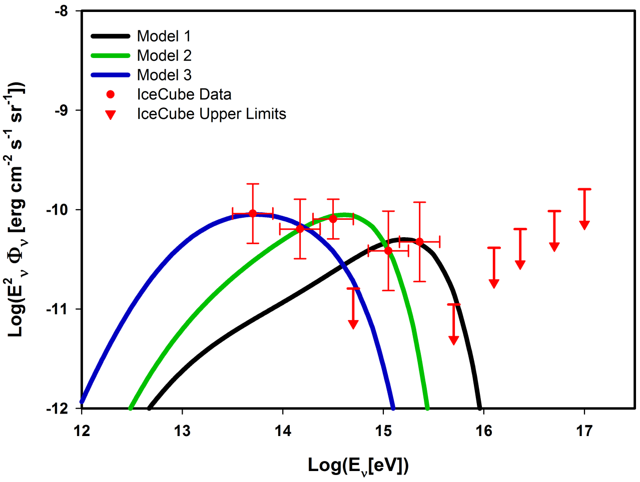


Figure 2: The calculated diffuse intensity of neutrinos in the radiogalaxies from magnetic reconnection model for three different models. The depicted Data are taken from IceCube measurements ([1]).

redshift for a class of astrophysical sources which is $z_{max} = 5.2$ for the radiogalaxies. The values for cosmological parameters are assumed as: $H_0 = 70$ km s^{-1}Mpc^{-1}, $\Omega_M = 0.3$ and $\Omega_\Lambda = 0.7$.

We derive the $\rho_\gamma(L_\gamma, z)$ from the radio luminosity function (RLF) obtained by [5] for misaligned AGNs which is given by

$$\rho(L_\gamma, z) = \rho_{r,tot}(L^{\rm 5GHz}_{r,tot}(L^{\rm 5GHz}_{r,core}(L_\gamma)), z) \times \frac{d\log L^{\rm 5GHz}_{r,core}}{d\log L_\gamma} \, \frac{d\log L^{\rm 5GHz}_{r,tot}}{d\log L^{\rm 5GHz}_{r,core}}. \tag{4.5}$$

The $d\log L^{\rm 5GHz}_{r,core}/d\log L_\gamma$ and $d\log L^{\rm 5GHz}_{r,tot}/d\log L^{\rm 5GHz}_{r,core}$ can be calculated by ([5])

$$\log L_\gamma = 2.00 \pm 0.98 + (1.008 \pm 0.025)\log(L^{\rm 5GHz}_{r,core}), \tag{4.6}$$

and

$$\log L^{\rm 5GHz}_{r,core} = 4.2 \pm 2.1 + (0.77 \pm 0.08)\log(L^{\rm 5GHz}_{r,tot}) \tag{4.7}$$

respectively. The $\rho_{r,tot}(L^{\rm 5GHz}_{r,tot}(L^{\rm 5GHz}_{r,core}(L_\gamma)), z)$ is the RLF that we found from the interpolation of the experimental data provide by [14] for the radiogalaxies which is

$$\begin{aligned} \rho_{r,tot}(L_r, z) = {} & (-1.1526 \pm 0.0411)\log L_r + (0.5947 \pm 0.1224)z \\ & + 23.2943 \pm 1.0558 \ \ {\rm Mpc}^{-3}(\Delta\log {\rm L}_{\rm 5GHz})^{-1}. \end{aligned} \tag{4.8}$$

Model dependence of resulting neutrino flux is shown in Figure 2, in which the dependence on the BH mass of the radiogalaxies causes the dependence on the maximum energy of accelerated protons. We calculate the diffuse neutrino intensity using magnetic reconnection model in the LLAGNs for three different reasonable typical values for their BH masses. The results are plotted in Figure 2 which are fitted with IceCube data.

In the first case (objects with $M_{BH} = 10^7 M_\odot$), the calculated spectrum implies that the most energetic detected neutrino by IceCube at $\sim$ 3PeV may originated from nuclear region of these LLAGNs as well as explaining the IceCube upper limit around 10PeV.

The calculated diffuse neutrino intensity in the case of radiogalaxies with the central BH mass of the order of $10^8 M_\odot$ (second model) can describe the spectrum of high energy neutrinos measured by IceCube in the range of $0.1-1$PeV.

As we show in Figure 2, the origin of detected IceCube neutrino in the narrow energy band of 5×10^{13}eV $-$ 0.1PeV and the IceCube upper limit at 5×10^{14}eV can be interpreted by photomeson production in the vicinity of BHs with mass of $\sim 10^9 M_\odot$ in radiogalaxies (third model).

For all three models sketched in Fig. 2, the calculated neutrino spectra have individual cut-off energies at three different energies as we expected earlier from Fig. 1.

5. Conclusions

- We have presented a reconnection acceleration model in the core region around the BH of the LLAGNs and showed that it is able to reproduced very well the detected neutrino spectrum by IceCube.
- Magnetic reconnection acceleration seems to provide a better efficiency in regions where magnetic activity is dominant in comparison with diffusive shock acceleration as the cores of LLAGNs. Particles can gain energy up to a few times $\sim$ 100 PeV due to magnetic reconnection acceleration.
- The observed PeV neutrinos may be originated in these cores via charged pion decays in hadronic processes.

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