Research Article

Dmitri L. Khokhlov*

Planck Neutrinos as Ultra High Energy Cosmic Rays

Abstract: The studied conjecture is that ultra high energy cosmic rays (UHECRs) are hypothetical Planck neutrinos arising in the decay of the protons falling onto the gravastar. The proton is assumed to decay at the Planck scale into positron and four Planck neutrinos. The supermassive black holes inside active galactic nuclei, while interpreted as gravastars, are considered as UHECR sources. The scattering of the Planck neutrinos by the proton at the Planck scale is considered. The Planck neutrinos contribution to the CR events may explain the CR spectrum from 5×10^{18} eV to 10^{20} eV. The muon number in the Planck neutrinos-initiated shower is estimated to be larger by a factor of 3/2 in comparison with the standard model that is consistent with the observational data.

Keywords: cosmic rays

1 Introduction

The origin of ultra high energy ($> 10^{18}$ eV) cosmic rays (UHECRs) is an open question (Kotera & Olinto 2011; Letessier-Selvon & Stanev 2011; Blasi 2013). UHECRs are believed to be protons (nuclei) accelerated in magnetized plasma outflows of astrophysical sources. The UHECRs are likely to originate in extragalactic sources, given the strength of Galactic magnetic fields and the lack of correlations with the Galactic plane. The potential UHECR candidate sources include cluster accretion shocks, active galactic nuclei (AGN), gamma ray bursts (GRBs), and neutron stars (NSs).

The UHECR energy spectrum presents two main features, the ankle at 5×10^{18} eV as measured by the Pierre Auger Observatory (PAO) (Valiño 2015) and by the Telescope Array (TA) experiment (Ivanov 2015), and the suppression at 4×10^{19} eV as measured by the PAO (Valiño 2015), and at 6×10^{19} eV as measured by the TA (Ivanov 2015). The ankle is a hardening in the spectrum, $\propto E^{-y}$, from a spectral index $y \approx 3.3$ to $y \approx 2.6$ as measured by the PAO (Valiño 2015), and from $y \approx 3.2$ to $y \approx 2.7$ as measured by the TA (Ivanov 2015). Above the suppression, the spectral index is $y \approx 5.7$ as measured by the PAO (Valiño 2015), and $y \approx 4.7$ as measured by the TA (Ivanov 2015). A comprehensive review of spectrum data, including other experiments, can be found in Gaisser et al. (2013).

The UHECR mass composition can be derived using the depth of shower maximum, X_{max}. The composition analysis based on X_{max} observed by the PAO shows the light component dominated composition around 10^{18} eV, and a gradual transition from light to heavy composition between $10^{18.3}$ eV and $10^{19.6}$ eV (Aab et al. 2014). The results obtained by the TA show the light component dominated composition from $\sim 10^{18}$ eV to $\sim 10^{20}$ eV (Abbasi et al. 2015).

The muon number measured by the PAO at energies in the range 4×10^{18} eV to 5×10^{19} eV is larger than the predicted one by 30–80 %, depending on the model (Aab et al. 2015a). The logarithmic gain is large compared to proton or iron showers that seems to suggest a transition from light to heavy composition but the excess of the measured muon number questions the interpretation of the composition.

The features in the UHECR spectrum may be caused by propagation losses if UHECRs are mostly protons. Propagating through CMB, UHE protons undergo photo-pion production, resulting in the GZK cut-off in the spectrum at $\approx 5 \times 10^{19}$ eV (Greisen 1966; Zatsepin & Kuzmin 1966), and pair-production, generating a hardening in the spectrum named dip, that reproduces quite well the ankle observed in the UHECR spectrum (Aloisio et al. 2007). The suppression in the end of the spectrum observed by PAO and TA is consistent with GZK cut-off. For a mixed composition of UHECRs, an explanation of both the PAO spectrum and mass composition at $\geq 5 \times 10^{18}$ eV requires hard injection spectra for all nuclei, $y = 1 – 1.6$, quite different from the spectra that are usually derived based on diffusive shock acceleration

Corresponding Author: D. L. Khokhlov: Sumy State University (Retired), Ukraine; Email: dlkhokhl@rambler.ru

at both non-relativistic and relativistic shocks (Aloisio et al. 2014; Taylor 2014); see, however, the model of highly-relativistic shocks (Meli et al. 2008) which gives spectra as flat as $y = 1.5$ for GRBs. When including the effect of extragalactic magnetic field, the combined-fit analysis using the PAO spectrum and mass composition found a soft injection spectrum, $y = 1.6 - 2.3$ (Wittkowski 2017).

Clarifying the structure of the region below 10^{18} eV is important to understand the UHECR origin; see a recent study (Thoudam et al. 2016) and references therein. The energy spectrum of CRs presents the features named the knee, a steepening from a spectral index $y \approx 2.7$ to $y \approx 3.1$ at 3×10^{15} eV, and the second knee, a steepening from a spectral index $y \approx 3.1$ to $y \approx 3.3$ above $\sim 10^{17}$ eV (Thoudam et al. 2016). The composition at the knee is dominated by light nuclei, and at the second knee, by heavy nuclei (Thoudam et al. 2016). The CRs with energies from the first knee to the second knee, are likely accelerated in supernova remnants of the Galactic origin (Thoudam et al. 2016). In this case, the knee signals the maximum energy for light nuclei, and the second knee, for heavy nuclei. Although this explanation is qualitatively in agreement with the observed CR spectrum from the first knee to the second knee, the predicted intensity is not enough and can explain only ~ 30 % of the observed intensity around the second knee (Thoudam et al. 2016). In the region 10^{17} eV to 10^{18} eV, observations revealed a strong light component, with the composition becoming lighter with energy. The origin of this light component is unknown. Several proposals to explain this light component are discussed (Thoudam et al. 2016) and references therein. KASCADE-Grande reported the CR composition between 10^{16} and 10^{18} eV, based on measurements of the ratio of electrons to muons (Apel et al. 2013). At 10^{17} eV, the flux of the heavy component predominates over the flux of the light component while, at 10^{18} eV, these are comparable.

Relativistic shock waves in AGN and GRBs have long been considered as prime candidates for the acceleration of CRs to the highest energies $\sim 10^{20}$ eV. However, investigations showed that particle acceleration at ultra-relativistic shock waves does not appear fast enough to produce UHECRs. In particular, in the case of the external shock of a GRB, the maximal energy is found to be $\sim 10^{16}$ eV (Plotnikov et al. 2013; Sironi et al. 2013; Reville & Bell 2014).

Based on their decay timescale, the UHECR sources can be grouped into two categories: steady, including AGN, quasar remnants, and transient, including GRBs, NSs, and giant AGN flares, see (Kotera & Olinto 2011) and references therein. Energetic requirements set a lower limit on single source luminosities, while the distribution of particle arrival directions in the sky sets a lower limit on the source

number density. By contrasting these limits with the luminosity functions from surveys of existing luminous steady objects in the nearby universe, Fang & Kotera (2016) excluded the steady proton sources at 95 % CL for UHECRs with energies $> 8 \times 10^{18}$ eV. They concluded that UHECRs with energies $> 8 \times 10^{18}$ eV are either iron-like heavy nuclei produced in steady sources, or generated in transient sources.

Lemoine & Waxman (2009) considered the following test. A source, emitting heavy nuclei of charge Z at an energy E, is expected to produce a similar anisotropy pattern at energies E/Z via the proton component associated with the same source. When applied to the PAO data (Abraham et al. 2007, 2008; Abreu et al. 2010), the test shows that the signal responsible for the apparent anisotropy pattern at energies $> 5.5 \times 10^{19}$ eV must not be heavy but light nuclei because the PAO does not see evidence for anisotropy at lower energies (Abraham et al. 2007).

Farrar & Gruzinov (2009) proposed that UHECRs may be produced by short duration AGN flares. However, such AGN flares should produce counterpart flares in X-rays through the concomitant acceleration of electrons (Waxman & Loeb 2009). Their non-detection by existing surveys strongly argues against such flaring scenarios.

The observation of secondary gamma rays and neutrinos, generated in the interactions undergone by the CRs during propagation through the universe, can constrain the UHECR models. The dip model, in which UHECRs above 10^{18} eV are mainly protons of extragalactic origin, has been rejected at 95 % CL (Heinze et al. 2016) by using the UHECR spectrum reported by the TA (Ivanov 2015) and the upper limit on the neutrino spectrum obtained by the IceCube experiment (Ishihara 2015). The null detection of neutrinos with energies well beyond PeV by the IceCube observatory has excluded the possibility that radio-loud AGN and/or GRBs are the origins of the highest energy cosmic rays $\sim 10^{20}$ eV if they are composed mainly of protons (Yoshida 2016). The neutrino production highly depends on the background density of the acceleration site. Several model had been considered, e.g. (Bustamante et al. 2015; Murase et al. 2012; Fang & Murase 2018), which allows radio-loud AGN and GRBs with dominant proton injections to be UHECR sources without violating the IceCube neutrino limits.

The Fermi-LAT observations (Ackermann et al. 2016) posit an upper limit on the diffuse gamma-ray flux generated via UHECR propagation. Focusing on the contribution of UHECRs at energies $(1 - 4) \times 10^{18}$ eV, where the composition is expected to be proton dominated, the diffuse gamma-ray flux generated through UHECR propagation has been calculated (Liu et al. 2016). When assuming the star formation rate (SFR) source evolution, the UHECR generated

flux is significantly higher than the Fermi-LAT upper limit. The problem has been studied for seven possible evolution models of UHECR sources (Gavish & Eichler 2016). Given the constraints imposed by the Fermi-LAT upper limit, the UHECR sources that evolve as the SFR, medium low luminosity AGN type-1 ($L = 10^{43.5}$ erg s^{-1} in the [0.5 – 2] keV band), and BL Lacs are the most acceptable. Under the assumption of UHECRs being mostly protons, there is not enough room for producing extragalactic UHECRs with AGN, GRB, SFR source evolution, and only BL Lacs source evolution is acceptable.

Berezinsky et al. (2016) studied the influence of the IceCube and Fermi-LAT restrictions on the source properties, such as evolution and distribution of sources, their energy spectrum and admixture of nuclei. They also studied the sensitivity of restrictions to various Fermi-LAT galactic foreground models, to the choice of extragalactic background light model and to overall normalization of the energy spectrum. They found viable proton and nuclei models, with relatively large generation index and not very large maximum redshift.

The combination of the foregoing constraints leaves little room for the proposed UHECR sources. In what follows we shall consider another possibility. Assume that UHECRs arise in the decay of the protons falling onto the gravastar. The gravastar (Mazur & Mottola 2004; Chapline 2003) is an alternative to black hole which contains a rigid surface instead of event horizon. To this end, several solutions to avoid the development of black hole event horizon within the classical theories have been discussed, e.g. (Corda & Mosquera Cuesta 2011) and references therein. The decay of the proton falling onto the gravastar was considered (Chapline 2003) within the $SU(5)$ theory of grand unification (Georgi & Glashow 1974), with the dominant mode of proton decay $p \rightarrow e^+\pi^0$ where the end products are positron and photons. An excess of 511 keV radiation from positron annihilation from the centre of the Galaxy (Prantzos et al. 2011) was explained (Barbieri & Chapline 2012) by the decay of the protons under their falling onto Sgr A* while interpreting Sgr A* as a gravastar. Khokhlov (2014) showed that the explanation is consistent with the accretion rate onto Sgr A* but predicts too high luminosity of Sgr A* in comparison with the observed one; see also the further investigation of the problem (Khokhlov 2017). Therefore, the photons are ruled out as proton decay products. One may consider another mode of the proton decay. The decay of proton at the Planck scale into positron and hypothetical Planck neutrinos, $p \rightarrow e^+4\nu_{Pl}$, was proposed in Khokhlov (2011). To this end, Planck neutrino may be considered as a dark matter candidate (Khokhlov 2015). The model of the galaxy with hot dark matter consisting of Planck neutrinos

can explain the rotation curves of the galaxies (Khokhlov 2018).

2 Planck neutrino spectrum

Consider the scenario in which UHECRs arise in the decay of the protons falling onto the gravastar. Assume that the proton decays at the Planck scale into positron and four hypothetical Planck neutrinos, $p \rightarrow e^+4\nu_{Pl}$, as it was proposed in Khokhlov (2011). Suppose that Planck neutrino is a massless particle which takes part in the interaction at the Planck scale (Newton gravity, scattering by the proton), and does not in the electromagnetic, weak and strong interactions. It may be hypothesized that Planck neutrinos, arising in the decay of the protons falling onto the gravastar, are UHECR particles. In what follows we shall study this conjecture. The supermassive black holes inside AGN, while interpreted as gravastars, will be considered as UHECR (Planck neutrino) sources.

Khokhlov (2017) considered a toy model of the proton falling onto the gravastar. The energy of the proton is split into two modes. The protons in the low level mode retain at the surface of the gravastar. The protons in the high level mode decay into positrons and Planck neutrinos. The energy of the proton in the high level mode is given by

$$E_+ = \frac{m_p}{(1 - 2GM/Rc^2)^{1/4}} \tag{1}$$

where m_p is the mass of proton, G is the Newton constant, c is the velocity of light, M and R are the mass and radius of the gravastar respectively. Khokhlov (2017) suggested that the energy released in the proton decay is converted into the energy of four Planck neutrinos while the energy of the positron remains non-relativistic. In general, this suggestion is not justified, and the positron acquires a part of the proton energy. Then, from the energy-momentum conservation it follows that the positron acquires 1/4 and four Planck neutrinos acquire 3/4 of the proton energy.

The radius of the gravastar is of the order of the Schwarzschild radius, $r_g = 2GM/c^2$. The velocity of the proton hitting the gravastar approaches near the speed of light thus giving a large kinetic energy of the proton. Assume that the energy of the proton hitting the gravastar is equal to the Planck energy

$$E_{Pl} = \frac{m_p}{(1 - 2GM/Rc^2)^{1/2}}. \tag{2}$$

With the use of eq. (2), the energy of the proton in the high level mode can be written in the form

$$E_+ = (m_p E_{Pl})^{1/2}. \tag{3}$$

From eq. (3), $E_+ = 3.4 \times 10^{18}$ eV. Thus, the energy released in the proton decay is 3.4×10^{18} eV. This gives the energy of four Planck neutrinos $(3/4) \times 3.4 \times 10^{18} = 2.5 \times 10^{18}$ eV.

Consider the scattering of the Planck neutrinos by the proton at the Planck scale. The interaction at the Planck scale is supposed to go through the tensor Planck field of the Planck mass (Khokhlov 2011). Keeping in mind $p \rightarrow e^+ 4\nu_{Pl}$, one can describe the process as

$$4\nu_{Pl} + p \rightarrow p + p + e^- \rightarrow 4\nu_{Pl} + p + e^+ e^-. \qquad (4)$$

In the process, four Planck neutrinos are scattered by a single proton, producing an electron-positron pair. The reaction [eq. (4)] goes in two stages. First, four Planck neutrinos transform into the proton. Then, the protons are scattered at the Planck scale.

The Lagrangian of the interaction at the Planck scale can be written in the form (Khokhlov 2011)

$$L \rightarrow \left(\frac{E}{m_{Pl}} \right)^2 \qquad (5)$$

where m_{Pl} is the Planck mass, E is the centre of mass energy, the coupling is taken to be unity. The cross-section of the transformation of the Planck neutrinos into the proton is given by

$$\left(\frac{E}{m_{Pl}} \right)^4. \qquad (6)$$

The cross-section of the scattering of the protons at the Planck scale is given by

$$\left(\frac{E}{m_{Pl}} \right)^2. \qquad (7)$$

Assume that four Planck neutrinos form the composite tensor field. This gives the factor, $1/2^4 = 1/16$, to the cross-section of the reaction. Suppose that the proton in the reaction [eq. (4)] is non-relativistic. Then, the centre of mass energy is $(E_\nu m_p)^{1/2}$, where E_ν is the energy of the Planck neutrinos. In view of eqs. (6,7), the probability of the reaction [eq. (4)] is given by

$$\frac{1}{\tau} = \frac{1}{16 t_{Pl}} \left(\frac{(E_\nu m_p)^{1/2}}{m_{Pl}} \right)^7 \qquad (8)$$

where t_{Pl} is the Planck time. The probability [eq. (8)] grows with the energy of the Planck neutrinos as $1/\tau \propto E_\nu^{3.5}$.

Consider CR events initiated by the Planck neutrinos in the scattering of the Planck neutrinos by air molecules. In the Planck neutrinos-proton scattering [eq. (4)], electron-positron pairs are produced. It is reasonable to think that electrons and positrons, arising in Planck neutrinos-air collisions, interact with air molecules, forming extensive air showers. The energy of four Planck neutrinos, arising in the decay of the proton falling onto the gravastar, is 2.5×10^{18} eV. The CR events initiated by four Planck neutrinos are thereby peaked at 2.5×10^{18} eV. Suppose that the energy distribution of Planck neutrinos above 2.5×10^{18} eV is described by the exponential law, $\exp[-(E_\nu/(2.5 \times 10^{18}$ eV$) - 1)]$. The probability of the scattering of the Planck neutrinos by the proton (neutron) of the air molecule is described by the power law, $E_\nu^{3.5}$. The combination of the two laws gives the Planck neutrino spectrum.

Due to the tensor nature of the reaction [eq. (4)], the number of the Planck neutrinos can be any multiple of four, $4k$ where k is an integer. Then, the energy of the CR events initiated by $4k$ Planck neutrinos can take the values $2.5k \times 10^{18}$ eV. The flux of $4k$ Planck neutrinos is a function of $1/k$. Also, in eq. (8) one should use the factor, $1/2^{4k}$. Suppose that the energy distribution of Planck neutrinos above $2.5k \times 10^{18}$ eV is described by the exponential law, $\exp[-(E_\nu/(2.5k \times 10^{18}$ eV$) - 1)]$. The probability of the scattering of the Planck neutrinos by the proton (neutron) of the air molecule is described by the power law, $E_\nu^{3.5}$, and the factor, $1/2^{4k}$. The factor, $1/k$, is due to the flux of the Planck neutrinos. The combination of the two laws and the two factors gives the Planck neutrino spectrum.

Assume that, at the ankle 5×10^{18} eV, the light component is dominant, and the Planck neutrino content in the CR composition is 0.1. Assume that, above 5×10^{18} eV, the light component is suppressed, and the Planck neutrino component becomes dominant. This may explain the ankle at 5×10^{18} eV as the transition from the light component dominated CRs to the Planck neutrino dominated CRs. Remind that the CR spectrum measured by the PAO (Valiño 2015) is described by the spectral index, $y \approx 2.6$, from the ankle 5×10^{18} eV to the suppression 4×10^{19} eV and $y \approx 5.7$ above the suppression 4×10^{19} eV. Consider CR events initiated by four, eight, twelve and sixteen Planck neutrinos peaked at 2.5×10^{18} eV, 5×10^{18} eV, 7.5×10^{18} eV and 10^{19} eV respectively. The Planck neutrinos can explain the CR spectrum measured by the PAO (Valiño 2015) from 5×10^{18} eV to 10^{20} eV, four Planck neutrinos from 5×10^{18} eV to 2.5×10^{19} eV, eight Planck neutrinos from 2.5×10^{19} eV to 5×10^{19} eV, twelve Planck neutrinos from 5×10^{19} eV to 8×10^{19} eV, sixteen Planck neutrinos from 8×10^{19} eV to 10^{20} eV.

The Planck neutrinos may initiate events at the IceCube neutrino observatory. Consider the constraint imposed by the IceCube on the Planck neutrino content in the CR composition at 5×10^{18} eV. The sensitivity of the IceCube for the Planck neutrinos may be taken from the CR spectrum of the PAO at 5×10^{18} eV, $\sim 1.2 \times 10^{24}$ eV^2 m^{-2} s^{-1} sr^{-1} Valiño (2015). Since 2008 the IceCube has detected no events

at 5×10^{18} eV (Ishihara 2015). The telescope area of the IceCube is 1 km^2. The non-detection of events at 5×10^{18} eV by the IceCube for 10 years gives the constraint < 0.006 on the Planck neutrino content in the CR composition at 5×10^{18} eV. This is less than the value 0.1 taken to fit the observed CR spectrum.

Compare the limits to the diffusive flux of UHE neutrinos by the IceCube (Ishihara 2015) and PAO (Aab et al. 2015b). All flavor neutrino flux differential sensitivity of the IceCube detector at 10^{18} eV is calculated to be $\leq 3 \times 10^{-9}$ GeV cm^{-2} s^{-1} sr^{-1} (Ishihara 2015). The model independent differential upper limit of the PAO at 10^{18} eV (single flavour neutrino flux ×3) is calculated to be 6×10^{-8} GeV cm^{-2} s^{-1} sr^{-1} (Aab et al. 2015b). This limit is 20 times more than that of the IceCube. With this in mind, the sensitivity of the IceCube for the Planck neutrinos may be less than that of the PAO. The low sensitivity of the IceCube in comparison with the PAO may be the reason of the non-detection of the Planck neutrino initiated events by the IceCube.

3 Muon number in the Planck neutrinos initiated shower

Consider the model of extensive air showers initiated by the Planck neutrinos. In the Heitler-Matthews model of extensive air showers (Matthews 2005), a cosmic ray proton of energy E_0 interacts with an air molecule and produces $r n_{mult}$ charged pions and $(1-r) n_{mult}$ neutral pions, where r is the pion charge ratio of hadronic interactions equal $2/3$, n_{mult} is the secondary particle multiplicity. Further interaction of the charged pions with air molecules gives rise to the formation of the hadronic cascade. The neutral pions decay instantaneously into 2γ which form the electromagnetic cascade. Charged pions decay into muons as soon as their energy drops below the critical energy of pions E_π^c. The muon number is given by

$$N_\mu = \left(\frac{E_0}{E_\pi^c} \right)^\beta \qquad (9)$$

with

$$\beta = \frac{\ln r n_{mult}}{\ln n_{mult}}. \qquad (10)$$

For $r = 2/3$, $\beta = 0.85$.

Consider the interaction of the Planck neutrinos with air molecules. At the first stage, the Planck neutrinos of energy E_0 interact with an air molecule and produce electron-positron pairs. At the second and all the following stages, the electrons and positrons interact with air molecules producing the charged and neutral pions that results in developing of the hadronic and electromagnetic cascades like in

the standard Heitler-Matthews model. In this scenario, the energy transferred to the electromagnetic cascade reduces. The muon number is given by

$$N_\mu = \frac{1}{r} \left(\frac{E_0}{E_\pi^c} \right)^\beta = \frac{E_0}{E_\pi^c}. \qquad (11)$$

The muon number [eq. (11)] is a linear function of the primary energy E_0, with $\beta = 1$. The value of the muon number is more by a factor of $1/r = 3/2$ than that in the standard model.

Some discrepancies have been reported by the PAO between observed and simulated muon content in the UHECR events (Aab et al. 2015a). The mean muon number observed in the hybrid measurement in highly inclined events at energies in the range 4×10^{18} eV to 5×10^{19} eV exceeds the expectations by $30 - 80$ %, depending on the model. The logarithmic gain $d \ln N_\mu / d \ln E$ of muons is measured to be $1.029 \pm 0.024 \pm 0.030$ (sys.). The logarithmic gain is large compared to proton or iron showers. This suggests a transition from lighter to heavier elements. The model under consideration predicts the muon number larger by a factor of $3/2$ in comparison with the standard model that is consistent with the observational data. The slope $\beta = 1$ predicted by the model under consideration is consistent with the logarithmic gain of muons observed by the PAO.

4 Conclusion

We have addressed the problem of the UHECR origin. We have assumed that UHECRs arise in the decay of the protons falling onto the gravastar. The proton has been considered to decay at the Planck scale into positron and four hypothetical Planck neutrinos. We have studied the conjecture that Planck neutrinos, arising in the decay of the protons falling onto the gravastar, are UHECR particles. The supermassive black holes inside AGN, while interpreted as gravastars, have been considered as UHECR sources.

We have considered the scattering of the Planck neutrinos by the proton at the Planck scale. In the process, four Planck neutrinos are scattered by a single proton, producing an electron-positron pair. The probability of the scattering is the seventh power over the energy, $(E/m_{Pl})^7$. In the case of the non-relativistic proton, the probability of the scattering grows with the energy of the Planck neutrinos as $E_\nu^{3.5}$.

We have considered CR events initiated by the Planck neutrinos in the scattering of the Planck neutrinos by air molecules. The energy of four Planck neutrinos, arising in the decay of the protons falling onto the gravastar, is

estimated to be 2.5×10^{18} eV. Due to the tensor nature of the scattering, the number of the Planck neutrinos can be any multiple of four, $4k$ where k is an integer. We have considered CR events initiated by four, eight, twelve and sixteen Planck neutrinos, peaked at 2.5×10^{18} eV, 5×10^{18} eV, 7.5×10^{18} eV and 10^{19} eV respectively. The combination of the laws, $\exp[-(E_\nu/(2.5k \times 10^{18}$ eV$) - 1)]$ and $E_\nu^{3.5}$, and the factors, $1/2^{4k}$ and $1/k$, gives the Planck neutrino spectrum above $2.5k \times 10^{18}$ eV. When assuming the Planck neutrino content 0.1 in the CR composition at 5×10^{18} eV, the Planck neutrinos can explain the CR spectrum measured by the PAO from 5×10^{18} eV to 10^{20} eV. The ankle in the CR spectrum at 5×10^{18} eV may be interpreted as the transition from the light component dominated CRs to the Planck neutrino dominated CRs.

The Planck neutrinos may initiate events at the Ice-Cube neutrino observatory. The non-detection of events at 5×10^{18} eV by the IceCube for 10 years gives the constraint < 0.006 on the Planck neutrino content in the CR composition at 5×10^{18} eV. This is less than the value 0.1 taken to fit the observed CR spectrum. The low sensitivity of the IceCube in comparison with the PAO may be the reason of the non-detection of the Planck neutrino-initiated events by the IceCube.

The model of extensive air showers initiated by the Planck neutrinos has been considered. Planck neutrinos-air collisions lead to the emergence of electrons and positrons which interact with air molecules producing the charged and neutral pions that results in developing of the hadronic and electromagnetic cascades. In this scenario, the muon number is a linear function of the primary energy, with the value larger by a factor of 3/2 in comparison with the standard model that is consistent with the observational data of the PAO.

References

Aab A, Abreu P, Aglietta M, Ahn EJ, Al Samarai I, Albuquerque IFM, et al. 2014. Depth of maximum of air-shower profiles at the Pierre Auger Observatory. I. Measurements at energies above $10^{17.8}$ eV. Phys Rev D Part Fields Gravit Cosmol. 90(12):122005.

Aab A, Abreu P, Aglietta M, Ahn EJ, Al Samarai I, Albuquerque IFM, et al. 2015a. Muons in air showers at the Pierre Auger Observatory: Mean number in highly inclined events. Phys Rev D Part Fields Gravit Cosmol. 91(3):032003.

Aab A, Abreu P, Aglietta M, Ahn EJ, Al Samarai I, Albuquerque IFM, et al. 2015b. Improved limit to the diffuse flux of ultrahigh energy neutrinos from the Pierre Auger Observatory. Phys Rev D Part Fields Gravit Cosmol. 91(9):092008.

Abbasi RU, Abe M, Abu-Zayyad T, Allen M, Anderson R, Azuma R, et al. 2015. Study of Ultra-High Energy Cosmic Ray composition

using Telescope Array's Middle Drum detector and surface array in hybrid mode. Astropart Phys. 64:49–62.

Abraham J, Abreu P, Aglietta M, Aguirre C, Allard D, Allekotte I, et al. 2007. Correlation of the highest-energy cosmic rays with nearby extragalactic objects. Science. 318(5852):938–943.

Abraham J, Abreu P, Aglietta M, Aguirre C, Allard D, Allekotte I, et al. 2008. Correlation of the highest-energy cosmic rays with the positions of nearby active galactic nuclei. Astropart Phys. 29(3):188–204.

Abreu P, Aglietta M, Ahn EJ, Allard D, Allekotte I, Allen J, et al. 2010. Update on the correlation of the highest energy cosmic rays with nearby extragalactic matter. Astropart Phys. 34(5):314–326.

Ackermann M, Ajello M, Albert A, Atwood WB, Baldini L, Ballet J, et al. 2016. Resolving the extragalactic γ-ray background above 50 GeV with the Fermi Large Area Telescope. Phys Rev Lett. 116(15):151105.

Aloisio R, Berezinsky V, Blasi P, Gazizov A, Grigorieva S, Hnatyk B. 2007. A dip in the UHECR spectrum and the transition from galactic to extragalactic cosmic rays. Astropart Phys. 27(1):76–91.

Aloisio R, Berezinsky V, Blasi P. 2014. Ultra high energy cosmic rays: Implications of Auger data for source spectra and chemical composition. J. Cosmol. Astropart. Phys.,2014(10):020.

Apel WD, Arteaga-Velázquez JC, Bekk K, Bertaina M, Blümer J, Bozdog H, et al. 2013. KASCADE-Grande measurements of energy spectra for elemental groups of cosmic rays. Astropart Phys. 47:54–66.

Barbieri J, Chapline G. 2012. Signature for the absence of an event horizon. Phys Lett B. 709(3):114–117.

Berezinsky V, Gazizov A, Kalashev O. 2016. Cascade photons as test of protons in UHECR. Astropart Phys. 84:52–61.

Blasi P. 2013. Theoretical challenges in acceleration and transport of ultra high energy cosmic rays: A review. EPJ Web of Conferences. 53:01002.

Bustamante M, Baerwald P, Murase K, Winter W. 2015. Neutrino and cosmic-ray emission from multiple internal shocks in gamma-ray bursts. Nat Commun. 6(1):6783.

Chapline G. 2003. Quantum phase transitions and the failure of classical general relativity. Int J Mod Phys A. 18(21):3587–3590.

Corda C, Mosquera Cuesta HJ. 2011. Irreversible gravitational collapse: black stars or black holes? Hadronic J. 34:149–159.

Fang K, Kotera K. 2016. The highest-energy cosmic rays cannot be dominantly protons from steady sources. ApJ. 832(1):L17.

Fang K, Murase K. 2018. Linking high-energy cosmic particles by black-hole jets embedded in large-scale structures. Nat Phys. 14(4):396–398.

Farrar GR, Gruzinov A. 2009. Giant AGN flares and cosmic ray bursts. ApJ. 693(1):329–332.

Gaisser TK, Stanev T, Tilav S. 2013. Cosmic ray energy spectrum from measurements of air showers. Front Phys. 8(6):748–758.

Gavish E, Eichler D. 2016. On ultra-high-energy cosmic rays and their resultant gamma-rays. ApJ. 822(1):56.

Georgi H, Glashow S. 1974. Unity of All Elementary-Particle Forces. Phys Rev Lett. 32(8):438–441.

Greisen K. 1966. End to the Cosmic-Ray Spectrum? Phys Rev Lett. 16(17):748–750.

Heinze J, Boncioli D, Bustamante M, Winter W. 2016. Cosmogenic neutrinos challenge the cosmic-ray proton dip model. ApJ. 825(2):122.

Ivanov, D. 2015. TA spectrum summary. Proceedings of the 34th International Cosmic Ray Conference, 2015 Jul 30- Aug 6, The Hague, The Netherlands. PoS. ICRC2015:349.

Ishihara A. 2015. A search for extremely high energy neutrinos in 6 years of IceCube data. Proceedings of the 34th International Cosmic Ray Conference, 2015 Jul 30- Aug 6, The Hague, The Netherlands. PoS. ICRC2015:1064.

Khokhlov, D. L. 2011. Gravitational wave in the theory with the universal charge. Open Astron. J., 4(SI 1):151–153. Available from: https://benthamopen.com/ABSTRACT/TOAAJ-4-151. DOI: 10.2174/1874381101004010151.

Khokhlov DL. 2014. Constraints on the decay of the protons falling onto Sgr A*. Phys Lett B. 729:1–2.

Khokhlov DL. 2015. Dark matter radiation from Sgr A*. Ap&SS. 360(1):27.

Khokhlov DL. 2017. Energy of the particle falling onto the surface of the Gravastar. Int J Mod Phys A. 4:8–11.

Khokhlov DL. 2018. Model of the galaxy with hot dark matter. Open Astron. 27(1):294–302. Available from: https://www.degruyter.com/view/journals/astro/27/1/article-p294.xml. DOI: https://doi.org/10.1515/astro-2018-0034.

Kotera K, Olinto AV. 2011. The astrophysics of ultrahigh-energy cosmic rays. Annu Rev Astron Astrophys. 49(1):119–153.

Lemoine M, Waxman E. 2009. Anisotropy vs chemical composition at ultra-high energies. J. Cosmol. Astropart. Phys. 11:009.

Letessier-Selvon A, Stanev T. 2011. Ultrahigh energy cosmic rays. Rev Mod Phys. 83(3):907–942.

Liu R-Y, Taylor AM, Wang X-Y, Aharonian FA. 2016. Indication of a local fog of subankle ultrahigh energy cosmic rays. Phys Rev D. 94(4):043008.

Matthews J. 2005. A Heitler model of extensive air showers. Astropart Phys. 22(5-6):387–397.

Mazur PO, Mottola E. 2004. Gravitational vacuum condensate stars. Proc Natl Acad Sci USA. 101(26):9545–9550.

Meli A, Becker JK, Quenby JJ. 2008. On the origin of ultra high Energy cosmic rays: Subluminal and superluminal relativistic shocks A&A, 492, 323–336.

Murase K, Dermer CD, Takami H, Migliori G. 2012. Blazars as ultrahigh-energy cosmic-ray sources: implications for TeV gamma-ray observations. ApJ. 749(1):63.

Plotnikov I, Pelletier G, Lemoine M. 2013. Particle transport and heating in the microturbulent precursor of relativistic shocks. MNRAS. 430(2):1280–1293.

Prantzos N, Boehm C, Bykov AM, Diehl R, Ferrière K, Guessoum N, et al. 2011. The 511 keV emission from positron annihilation in the Galaxy. Rev Mod Phys. 83(3):1001–1056.

Reville B, Bell AR. 2014. On the maximum energy of shock accelerated cosmic rays at ultra-relativistic shocks. MNRAS. 439(2):2050–2059.

Sironi L, Spitkovsky A, Arons J. 2013. The maximum energy of accelerated particles in relativistic collisionless shocks. ApJ. 771(1):54.

Taylor AM. 2014. UHECR composition models. Astropart Phys. 54:48–53.

Thoudam S, Rachen JP, van Vliet A, Achterberg A, Buitink S, Falcke H, et al. 2016. Cosmic-ray energy spectrum and composition up to the ankle: The case for a second Galactic component. A&A. 595:A33.

Valiño I. 2015. The flux of ultra-high energy cosmic rays after ten years of operation of the Pierre Auger Observatory. Proceedings of the 34th International Cosmic Ray Conference, 2015 Jul 30- Aug 6, The Hague, The Netherlands. PoS. ICRC2015:271.

Waxman E, Loeb A. 2009. Constraints on the local sources of ultra-high-energy cosmic rays. J. Cosmol. Astropart. Phys. 2009(08):026.

Wittkowski, D. for the Pierre Auger Collaboration. Reconstructed properties of the sources of UHECR and their dependence on the extragalactic magnetic field. Proceedings of the 35th International Cosmic Ray Conference, 2017 Jul 10 - Jul 20, Bexco, Busan, Korea. PoS. ICRC2017: 563.

Yoshida S. 2016. What have we learned about the sources of ultrahigh-energy cosmic rays via neutrino astronomy? Available from: arXiv:1612.04934.

Zatsepin G, Kuzmin V. 1966. Upper limit of the spectrum of cosmic rays. JETP Lett. 4:78.