Physical Science International Journal

24(2): 50-58, 2020; Article no.PSIJ.55827

ISSN: 2348-0130

Consequences of Massive Neutrino to Astrophysics and Cosmology

E. Comay[1*]

[1]*Charactell Ltd., P.O.Box 39019, Tel-Aviv, 61390, Israel.*

Author's contribution

The sole author designed, analysed, interpreted and prepared the manuscript.

Article Information

DOI: 10.9734/PSIJ/2020/v24i230178

Editor(s):

(1) Dr. Horacio S. Vieira, University of São Paulo, Brazil.

(2) Dr. Roberto Oscar Aquilano, National University of Rosario (UNR), Argentina.

Reviewers:

(1) Ricardo Luís Lima Vitória, Universidade Federal do Pará, Brazil.

(2) Sie Long Kek, Universiti Tun Hussein Onn Malaysia, Malaysia.

(3) Alejandro Gutierrez-Rodriguez, Universidad Autonoma de Zacatecas, México.

(4) Pipat Chooto, Prince of Songkla University, Thailand.

(5) Theocharis S. Kosmas, University of Ioannina, Greece.

Complete Peer review History: http://www.sdiarticle4.com/review-history/55827

Received 03 February 2020

Accepted 07 April 2020

Published 11 April 2020

Review Article

ABSTRACT

It is now recognized that a neutrino is a massive spin-1/2 particle. Consequently, neutrino-antineutrino pair production and their pair annihilation are theoretically valid processes. The data prove that the strength of weak interactions increases with collision energy. Therefore, a neutrino pair production event is expected to be a significant process in the region which is just outside the event horizon of a black hole. Another neutrino source is the pair production of particles like muons and charged pions whose decay produces neutrinos. Similarly, copious neutrino pair production events are expected to take place right after the big bang. Since a neutrino does not directly participate in electromagnetic interactions, its pair annihilation cannot directly produce photons. For this reason, a low energy neutrino-antineutrino collision can only go to another neutrino-antineutrino pair. It follows that the number of low energy neutrinos increases with time. This effect may contribute to the problem of the missing mass of the universe.

Keywords: Neutrinos; dark matter; gravitation; black holes.

ORCID: 0000-0003-1637-6494

**Corresponding author: E-mail: elicomay@post.tau.ac.il;*

1 INTRODUCTION

The positron was discovered in the very early days of quantum theory. This discovery has established the pair production attribute of a Dirac particle (see [1], p. 5). In principle, if the excitation energy of an appropriate system of interacting particles or the kinetic energy of two colliding particles is higher than the sum of the electron-positron mass then an electron-positron pair production effect may take place. Pair annihilation is a corresponding effect where an electron and a positron destroy each other. The decay of the positronium into two or three γ photons demonstrates this effect. An analogous example is the electron-positron annihilation and the Z-boson production $e^+e^- \rightarrow$ Z at collision energy that is close to 91 GeV (see [2], pp. 428-434).

Pair production and pair annihilation are a general property of Dirac particles. For example, the decay channel of the Z boson $Z \rightarrow \mu^+\mu^-$ is an example of muon pair production [3]. Furthermore, quarks are spin-1/2 particles, and, in principle, a meson production is a pair production of a $\bar{q}q$ bound state (see e.g. [2], p. 252). Thus, the decay of the baryon $\Delta(1232) \rightarrow N\pi$ [3] is an example of an excited baryonic state that decays into a nucleon and a pion, where the pion is a bound state of a $\bar{q}q$ pair. Similarly, the decay $\pi^0 \rightarrow 2\gamma$ [3] is an example of a $\bar{q}q$ pair annihilation. For a discussion of $\bar{q}q$ pair annihilation, see also [4], p. 294.

It is now recognized that "neutrinos can no longer be considered as massless particles" [5]. Here is a quotation indicating that the concept of a massive neutrino is already accepted by the general community: "The Nobel Prize in Physics 2015 recognizes Takaaki Kajita in Japan and Arthur B. McDonald in Canada, for their key contributions to the experiments which demonstrated that neutrinos change identities. This metamorphosis requires that neutrinos have mass. The discovery has changed our understanding of the innermost workings of matter and can prove crucial to our view of the universe" [6].

The neutrino mass affects many physical properties of this particle. One result of this evidence is that, like the case of other Dirac particles, the pair production effect should also hold for neutrinos. The present work is dedicated to an analysis of the physical and astrophysical consequences of this process. The concept of a massive neutrino was established only 20 years ago [6]; however, the very small upper bound on its mass was published only a few years ago [7]. This progress increases the experimental basis of the concept of neutrino pair production.

The problem of neutrino pair production effect is discussed in the literature (see e.g. [8, 9, 10, 11]). However, unlike the case of electrically charged leptons and quarks, there are quite a few textbooks and review articles that refrain from a discussion of the neutrino pair production issue (see e.g. [1, 2, 5, 4]). For this reason, the neutrino pair production and pair annihilation processes deserve a more extensive discussion. The present work shows relationships between data of neutrino mass and astronomical measurements that indicate the existence of a missing mass in the universe, and describes some new aspects of this issue.

Units where $\hbar = c = 1$ are used. Greek indices run from 0 to 3. Most formulas take the standard form of relativistic covariant expressions. The metric is diagonal and its entries are (1,-1,-1,-1). Following the first part of the introduction, the second section explains why the electroweak theory is not used in the analysis presented herein. The third section examines the physical properties of neutrinos. The fourth section shows neutrino sources that exist in the universe. The fifth section discusses the astrophysical consequences of neutrinos. The last section summarizes this work.

2 INHERENT CONTRADICTIONS OF THE ELECTROWEAK THEORY

The neutrino analysis that is carried out below does not rely on the electroweak theory. The reason is that it has recently been proved that this theory suffers many uncorrectable contradictions (see e.g. section 3 of [12] and references therein). Here are a few examples that substantiate this matter.

1. The factor $(1 \pm \gamma^5)$ is an important quantity of the electroweak theory, and it agrees with a massless neutrino. The literature substantiates the relation between a massless neutrino and the electroweak theory. Indeed, the factor $(1 \pm \gamma^5)$ is associated with "a neutrino which travels exactly with the velocity of light" [13]. A review article restates the neutrino masslessness attribute of the electroweak theory: "Two-component left-handed massless neutrino fields play crucial role in the determination of the charged current structure of the Standard Model" (see the Abstract of [14]). Similarly, a textbook says: "Neutrino masses are exactly zero in the Standard Model" (see [15], p. 533).

   As shown in the introduction, experiments already refute this electroweak element. Furthermore, the unitary representations of the inhomogeneous Lorentz group were analyzed by Wigner (see [16, 17, 18]). The result of his work revealed that a massive particle and a massless particle belong to different categories. The following argument indicates that this is quite an obvious result. Indeed, there is a Lorentz frame for a massive particle where it is instantaneously at rest. There is no such frame for a massless particle.

   It can be concluded that the progress of experimental physics refutes the electroweak concept of a massless neutrino.

2. A physical theory is unacceptable if it fails to satisfy vital requirements. Here are two issues that electroweak theory textbooks do not mention:

   2.1 Let us examine Maxwellian electrodynamics and the electrically charged $W^\pm$ bosons that are essential elements of the electroweak theory. "The equations governing electromagnetic phenomena are the Maxwell equations" (see [19], p. 2). Charge conservation is a crucial element of Maxwellian electrodynamics, and the continuity equation

$$j^\mu_{,\mu} = 0 \tag{1}$$

   is the mathematical form of this principle (see [20], pp. 76, 77). Here j^μ denotes the 4-current of the electric charge. The Dirac equation satisfies charge conservation (see [21], p. 24). It is interesting to note that a consistent expression for a conserved 4-current of the Dirac equation of the electron (and of its associated density) was found about one month after the publication of this equation [22, 23]. By contrast, the electroweak theory of the charged $W^\pm$ bosons is about fifty years old and this theory still has no expression that proves charge conservation of these bosons. Indeed, important research centers like Fermilab and CERN use *an effective expression* for the $W^\pm$ electromagnetic interaction [24, 25].

   This evidence proves that the electroweak theory violates Maxwellian electrodynamics.

   2.2 Physics contains successful theories that describe the interaction between physical objects. The general structure of these theories relies on a Lagrangian function whose Euler-Lagrange equations are those of the motion of the relevant physical objects. Successful physical theories are characterized by the fact that solutions of their equations of motion appropriately describe the time-evolution of the relevant particles.

   This structure holds for Maxwellian electrodynamics and the Dirac theory of electrically charged spin-1/2 particles, like the electron. The non-relativistic limit of the Dirac equation – the Pauli equation (see [21], pp. 11-13) and the Schroedinger equation (see any textbook on quantum mechanics) – are useful in science and technology.

By contrast, no textbook shows *an explicit form* of the electroweak equations of motion! A fortiori, no solution is derived for these unknown equations.

(Perhaps the reason for this vital flaw is that the explicit form of the electroweak Lagrangian density comprises more than 20 terms (see e.g. [26], p. 518; [27]). Hence, the explicit form of the corresponding Euler-Lagrange equations should look like a mess. By contrast, the standard form of the Lagrangian density of a Dirac particle and electromagnetic fields comprises just three terms

$$\mathcal{L}_{QED} = \bar{\psi}(\gamma^\mu i\partial_\mu - m)\psi \\ -\frac{1}{16\pi}F^{\mu\nu}F_{\mu\nu} - e\bar{\psi}\gamma^\mu A_\mu\psi. \quad (2)$$

Here the first term represents a free Dirac particle, the second free electromagnetic fields and the third electromagnetic interaction of a charged Dirac particle (see [28], p. 84; [29], p. 78).)

The lack of equations of motion and their solution is another serious flaw of the electroweak theory.

These problems justify the approach of this work which ignores the electroweak theory and derives neutrino properties from experimental data.

3 NEUTRINO PROPERTIES

Let us examine the neutrino's physical properties. Excluding gravitation, a neutrino participates only in weak interactions. This section examines the neutrino weak interactions.

The physical properties of weak interactions differ from the corresponding properties of strong and electromagnetic interactions. Parity violation and flavor violation are well-known properties of weak interaction. These effects enable the detection of a weak interaction process in cases that are forbidden by strong and electromagnetic interactions, like the β decay of nuclei and the decay of the K meson.

Several kinds of experimental data show that the energy-dependence of a weak process differs from that of electromagnetic and strong interaction processes:

1. At low energy, weak interactions are really weak and they are found *only* in a process that is forbidden by strong and electromagnetic interactions. Here the time duration of a weak process is many orders of magnitude longer than that of a typical strong and electromagnetic process (see [1], p. 207). The lifetime of a process increases with the decrease of the strength of the relevant force. (The relative strength of the weak force at these circumstances is the reason for the name *weak interactions*.)
2. The energy-dependence of the cross-section of a scattering process that is dominated by electromagnetic interactions is different from the case where the scattering is dominated by weak interactions. Thus, let us compare the electron and the neutrino scattering data. The electron's electromagnetic cross-section decreases with the increase of energy (see [1], chapter 6), whereas the total cross-section of the weak interaction of neutrino scattering per nucleon increases with energy (see [5], p. 1323). It means that at high enough energy a weak interaction effect is expected to become quite powerful. (Here the term *powerful* means strong, and its usage aims to avoid confusion with the ordinary strong interactions.) This argument uses neutrinos as pure sensors of weak interactions. However, the powerful attribute of high energy weak interactions applies to all Dirac particles.
3. The data on electron-positron collision that produces quarks $e^+e^- \to \bar{q}q$ show that at the energy of about 200 GeV, the relative strength of weak interactions is several

times *stronger* than the electromagnetic interactions (see fig. 16.2 on p. 430 of [2]).

4. Let us examine the experimental results of proton-proton cross-section measurements [30]. The figure includes data of a very large energy range and the energy of a cosmic ray proton is about 10^5 times greater than that of the Large Hadron Collider of CERN (the international research organization based in Geneva, Switzerland) where the latter is the highest energy produced in laboratories. It means that there are regions in the universe where the energy of particle interaction is extremely high. The space just outside the event horizon of a black hole is a plausible candidate for this kind of region [31, 32, 33]. The previous arguments indicate that weak interaction processes are expected to take place in such a region. Referring to neutrino production, this process may be a direct $\bar{\nu}\nu$ pair production or a secondary neutrino production process, like that of the charged pion decay sequence [3]

$$\pi^- \to \mu^- \bar{\nu}_\mu$$
$$\mu^- \to e^- \bar{\nu}_e \nu_\mu. \tag{3}$$

There are other aspects of neutrino interactions. As stated in the introduction, pair production also applies to neutrino interactions. The data show that the neutrino mass is much smaller than that of the electron. Recent neutrino measurements indicate that the upper bound of its mass is significantly smaller than 1 eV [7], namely, smaller than 10^{-6} times the electronic mass. Moreover, each flavor of quarks and leptons participate in weak interactions. The neutrino tiny mass means that neutrino pair production is an effect that may take place in many scattering events.

The neutrino pair annihilation requires a special examination. A neutrino does not participate in electromagnetic interactions. For example, the upper bound of the neutrino magnetic moment is smaller than 10^{-10} μ_B [3]. (It means that the strength of a $\bar{\nu}\nu$ magnetic interaction must be smaller by a factor of 10^{-20} with respect to the corresponding interaction of electrons.) Hence, a $\bar{\nu}\nu$ pair cannot directly decay into photons. It follows that a neutrino pair annihilation must go into a pair of Dirac particles. Therefore, ignoring higher-order processes, a collision of two neutrinos whose invariant mass is less than $2M_e = 1.022$ MeV can only go to another pair (or pairs) of neutrinos. (Here M_e denotes the electronic mass.) This restriction means that at the ordinary region of the universe, the number of appropriately low energy neutrinos does not decrease. On the other hand, neutrinos pair production may take place in a collision of cosmic rays of protons, electrons, and neutrinos with other neutrinos that already exist in the universe.

This discussion indicates that the number of neutrinos in the universe increases with time.

The neutrino tiny mass yields another attribute of this particle: Except at the very low energy region, its motion is extremely relativistic. Evidently, this neutrino velocity is larger than the escape velocity of cosmological bodies, except places like the inner region of a black hole. Hence, free neutrinos are expected to be found in the galactic and intergalactic space.

4 NEUTRINO SOURCES IN THE UNIVERSE

Experiments prove that a neutrino production effect is found in many natural processes of the present state of the universe. Here is a list of this kind of event.

1. Many non-artificial nuclear isotopes undergo a β-decay. The decay of a free neutron
$$n \to p + e^- + \bar{\nu}_e \tag{4}$$
is an example of such a process (see [34], p. 23). Another example is the decay of the carbon isotope
$$^{14}C \to \,^{14}N + e^- + \bar{\nu}_e. \tag{5}$$
Every nuclear β-decay produces a neutrino or an antineutrino.
2. Pions are produced by an energetic collision, for example, by cosmic rays in the upper atmosphere. It is shown in (3) that neutrinos are emitted in the decay chain of a charged pion.

3. Nuclear reactions take place in stars like the sun. One result of these reactions is a neutrino emission (see [34], p. 366).
4. A supernova is a dramatic collapse of a star under its gravitational force. Here protons eventually capture electrons and convert into neutrons. Neutrinos are emitted in this process (see [34], pp. 381, 382). The neutrinos emitted from the supernova 1987A that were detected on earth confirm this interpretation of a supernova process.
5. Galactic sources of high energy neutrinos that are produced by binary stars where one of them is a compact object are discussed [35, 36]. These systems are called microquasars.
6. Extremely high energy processes take place at the spatial region just outside the event horizon of a black hole. In principle, pair production of all kinds of Dirac particles should be found in this region. The above-mentioned powerful property of weak interactions at extremely high energy indicates that in this energy region the neutrino pair production is not a negligible effect. Besides this effect, pair production of particles like muons and charged pion production yield particles whose decay mode contains neutrinos (3). Furthermore, the tiny neutrino mass proves that, relative to other massive particles, neutrinos are more likely to escape this region. These arguments explain why the outer part of a black hole is expected to be a "neutrino factory".

   It is interesting to note that the IceCube collaboration has recently reported a detection of an extremely high energy neutrino that has been emitted from a known blazar [37]. This event may result from a direct neutrino pair production or from a decay sequence like that of a charged pion (3). In either case, it shows that very high energy neutrinos are produced in the outer region of a black hole.
7. These arguments mean that the neutrino population of the universe may be a non-negligible phenomenon. Therefore, high energy cosmic rays of protons, heavier nuclei and leptons may interact with these neutrinos and produce neutrino pair production events.

Items 1-7 point out neutrino production in the present state of the universe. Evidently, a copious amount of neutrinos are expected to be produced shortly after the big bang event.

As explained in the previous section, a pair of neutrino-antineutrino whose energy is less than 1.022 MeV cannot disappear. It means that low energy neutrinos accumulate in the universe. Due to their extremely tiny mass, a considerable portion of these neutrinos move relativistically. For this reason, they are evenly populated in galactic and intergalactic space. However, general considerations indicate that the density of extremely low-energy neutrinos is higher at the galactic inner region.

5 ASTROPHYSICAL CONSEQUENCES

Astronomical observations indicate that galactic stars and their black holes cannot explain galactic gravitational phenomena. Referring to this issue, a review article states that "a general picture emerges, where both baryonic and non-baryonic dark matter is needed to explain current observations" [38]. One kind of the missing matter is called *Cold Dark Matter* (CDM). "CDM is thought to consist of particles (sometimes referred to as 'exotic' dark-matter particles) whose interactions with ordinary matter are so weak that they are seen primarily via their gravitational influence" (see [39] p. 306,[40]). A candidate for the missing matter is called *Weakly Interaction Massive Particles* (WIMP) [3]. An experimental search for WIMPs is carried out for several decades, but there is still no confirmation of the existence of relatively massive WIMPs.

Neutrinos are mentioned in [38, 39, 40] as possible candidates for a part of the missing mass of the universe. The present work which depends on the relatively new concept of massive neutrinos changes the picture. Considering a neutrino as an ordinary Dirac particle, the above-mentioned pair production effect together with the blocked channel of low energy neutrino pair annihilation indicate that the neutrino population of the universe may be quite significant and that their role should not be ignored.

Another astrophysical problem is the geometrical structure of the universe. This issue depends on the space-time curvature that is derived from a general relativistic treatment of the distribution of the entire energy/mass of the universe. It turns out that the global structure of the universe is still an open problem. For example, a recently published article addresses this issue and argues that gravitational curvature renders a closed universe [41]. Another discussion of the structure of a closed universe can be found in the literature [42]. By contrast, other articles that have been published in the new millennium argue that the universe is flat [43, 44]. This work describes new arguments that support the existence of galactic and intergalactic neutrino populations and the gravitational field of these neutrinos may be used for the clarification of this open problem.

6 CONCLUSIONS

This work uses the relatively new evidence where neutrinos are massive Dirac particles. Neutrino pair production is one result of this issue. The data show that at very high energy the intensity of weak interactions becomes quite powerful. Hence, a neutrino pair production in regions of space that are close to the event horizon of a black hole is quite a significant process. Furthermore, the decay of particles like charged pions and muons produce neutrinos. A fortiori, neutrino production during the big bang epoch is expected to be quite a significant process as well. On the other edge of the energy scale, the irrelevance of neutrino electromagnetic interactions means that for a very low energy neutrino collision, a neutrino pair annihilation can only go into a neutrino pair production. It can be concluded that outside black holes, the neutrino population of the universe is expected to increase with time.

Pauli proposed the neutrino about 90 years ago and its detectability has made progress since then. At present energetic neutrinos can be detected by devices, whereas low energy neutrinos are still directly undetectable. However, the theoretical arguments that are described above indicate the existence of low energy neutrinos that are roaming elusively throughout the universe.

Astrophysical evidence indicates the existence of a dark matter in the universe [39, 40]. It turns out that the search for very massive WIMPs has not confirmed their existence [3]. However, if one takes literally the term WIMP then a massive neutrino is a WIMP. The present work explains why neutrinos may be regarded at least as a part of the missing dark matter.

COMPETING INTERESTS

Author has declared that no competing interests exist.

REFERENCES

[1] Perkins DH. Introduction to high energy physics. Menlo Park CA: Addison-Wesley; 1987.

[2] Thomson M. Modern particle physics. Cambridge: Cambridge University Press; 2013.

[3] Tanabashi M, et al. (Particle Data Group), Review of particle physics. Phys. Rev. D. 2018;98(030001):1-1989.

[4] Griffiths D. Introduction to elementary particles, 2nd ed. Weinheim: Wiley-VCH; 2008.

[5] Formaggio JA, Zeller GP. From eV to EeV: Neutrino cross sections across energy scales. Rev. Mod. Phys. 2012;84:1307-1341.

[6] The nobel prize in physics 2015. Available:https://www.nobelprize.org/prizes/-physics/2015/press-release/

[7] Mertens S. Journal of Physics: Conference Series. Direct neutrino mass experiments. 2016;718(022013):1-9. Available:https://iopscience.iop.org/article/-10.1088/1742-6596/718/2/022013/pdf

[8] Steigman G. Neutrino pair production in bound-bound transitions. Phys. Rev. 1966;151:1189-1191.

[9] Konashi H, Konashi K, Shigemoto K. Neutrino pair production in e^+e^- collision: A method for neutrino distinction and family counting. Lett. Nuovo Cimento. 1982;35:423-426. Available:https://link.springer.com/article/-10.1007/BF02754763

[10] Ch. Zhukovskii V, Grigoruk AE, Levtchenko KG, Eminov PA. Neutrino pair production by a virtual photon in an external magnetic field. Available:https://arxiv.org/abs/hep-ph/9810342

[11] Lobanov AE. Neutrinoantineutrino pair production by a photon in a dense matter. Phys. Lett. B. 2006;637:274-278.

[12] Comay E. Differences between two weak interaction theories. PSIJ. 2019;21:1-9. Available:http://www.journalpsij.com/-index.php/PSIJ/article/view/30091

[13] Salam A. Nobel Lecture. Available:https://www.nobelprize.org/-uploads/2018/06/salam-lecture.pdf

[14] Bilenky SM. Neutrino in standard model and beyond. Phys. Part. Nuclei. 2015;46:475-496.

[15] Srednicki M. Quantum field theory. Cambridge: Cambridge University Press; 2007.

[16] Weinberg S. The quantum theory of fields. Vol. I. Cambridge: Cambridge University Press; 1995.

[17] Wigner E. On unitary representations of the inhomogeneous lorentz group. Ann. Math. 1939;40:149-204. Available:http://www.jstor.org/stable/1968551

[18] Schweber SS. An introduction to relativistic quantum field theory. New York: Harper & Row. 1964;44-53.

[19] Jackson JD. Classical electrodynamics. New York: John Wiley; 1975.

[20] Landau LD, Lifshitz EM. The classical theory of fields. Amsterdam: Elsevier; 2005.

[21] Bjorken JD, Drell SD. Relativistic quantum mechanics. New York: McGraw-Hill; 1964.

[22] Dirac PAM. The quantum theory of the electron. Proc. Roy. Soc. Lond. 1928;A117:610-624. Available:https://www.jstor.org/stable/94981?seq=1metadata-info-tab-contents

[23] Darwin CG. The wave equations of the electron. Proc. Roy. Soc. Lond. A. 1928;118:654-680. Available:https://doi.org/10.1098/rspa.-1928.0076

[24] Abazov VM, et al. (D0 collaboration), Limits on anomalous trilinear gauge boson couplings from WW, WZ and Wγ production in p$\bar{\text{p}}$ collisions at $\sqrt{S} = 1.96$ TeV. Phys. Lett. B. 2012;718:451-459.

[25] Aad G, et al. (ATLAS Collaboration), Measurement of the WW cross section in $\sqrt{S} = 7$ TeV pp collisions with the ATLAS detector and limits on anomalous gauge couplings. Phys. Lett. B. 2012;712:289-308.

[26] Sterman G. An Introduction to quantum field theory. Cambridge: Cambridge University Press; 1993.

[27] A Wikipedia item. Available: https://en.wikipedia.org/wiki/Electroweak-interactionAfter-electroweak-symmetry-breaking

[28] Bjorken JD, Drell SD. Relativistic quantum fields. New York: McGraw-Hill; 1965.

[29] Peskin ME, Schroeder DV. An introduction to quantum field theory. Reading Mass: Addison-Wesley; 1995.

[30] Tanabashi M, et al. (Particle Data Group), Review of particle physics. Phys. Rev. D. 2018;98(030001):1-1989. Available:http://pdg.lbl.gov/2019/reviews/-rpp2019-rev-cross-section-plots.pdf

[31] A Wikipedia item. Available:https://en.wikipedia.org/wiki/Black-hole

[32] A Wikipedia item. Available:https://en.wikipedia.org/wiki/Quasar

[33] A Wikipedia item. Available:https://en.wikipedia.org/wiki/Blazar

[34] Wong SSM. Introductory Nuclear Physics. New York: Wiley; 1998.

[35] Smponias T, Kosmas OT. High energy neutrino emission from astrophysical jets in the galaxy. Advances in High Energy Physics. 2015;1-7. Article ID 921757
Available:http://downloads.hindawi.com/-journals/ahep/2015/921757.pdf

[36] Smponias T, Kosmas O. Neutrino emission from magnetized microquasar jets. Advances in High Energy Physics. 2017;1-7. Article ID 4962741
Available:http://downloads.hindawi.com/journals/ahep/2017/4962741.pdf

[37] The Ice cube collaboration. Ice Cube neutrinos point to long-sought cosmic ray accelerator; 2018.
Available:https://icecube.wisc.edu/news/-view/586

[38] Bergstrom L. Non-baryonic dark matter: Observational evidence and detection methods. Rep. Prog. Phys. 2000;63:793-841.
Available:https://iopscience.iop.org/article/-10.1088/0034-4885/63/5/2r3/pdf

[39] Overduin JM, Wesson PS. Dark matter and background light. Phys. Rep. 2004;402:267-406.
Available:https://www.sciencedirect.com/journal/physics-reports/vol/402/issue/5

[40] A Wikipedia item.
Available:https://en.wikipedia.org/wiki/Dark-matter

[41] Di Valentino E, Melchiorri A, Silk J. Planck evidence for a closed Universe and a possible crisis for cosmology. Nature Astronomy. 2019;4:196-203.
Available:https://www.nature.com/articles/-s41550-019-0906-9.pdf

[42] Luminet JP, Weeks J, Riazuelo A, Lehoucq R, Uzan JP. Dodecahedral space topology as an explanation for weak wide-angle temperature correlations in the cosmic microwave background. Nature. 2003;425:593-595.
Available:https://arxiv.org/abs/astro-ph/0310253

[43] A NASA publication.
Available:https://map.gsfc.nasa.gov/universe/uni-shape.html

[44] Vardanyan M, Trotta R, Silk J. How flat can you get? A model comparison perspective on the curvature of the Universe. Monthly Notices of the Royal Astronomical Society. 2009;397(1):31-444.
Available:https://academic.oup.com/mnras/-article/397/1/431/1006985

Peer-review history:
The peer review history for this paper can be accessed here:
http://www.sdiarticle4.com/review-history/53449