DECLARATION

I, Sabyasachi Ray, declare that this thesis titled, "**STUDYING THE ORIGIN OF COSMIC RAYS THROUGH TeV-PeV ENERGY NEUTRINOS AND GAMMA RAYS**" has been prepared by me under the guidance of **Dr. Rajat K. Dey**, Associate Professor of Department of Physics, University of North Bengal. No part of this thesis has formed the basis for the award of any degree or fellowship previously.

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It is certified that the work contained in the thesis titled **"STUDYING THE ORIGIN OF COSMIC RAYS THROUGH TeV-PeV ENERGY NEUTRINOS AND GAMMA RAYS,"** submitted by **"Mr. Sabyasachi Ray,"** has been carried out under my supervision and that this work has not been submitted elsewhere for any degree or diploma.

07.09.2023

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Date:7th September 2023

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STUDYING THE ORIGIN OF COSMIC RAYS THROUGH TeV-PeV ENERGY NEUTRINOS AND GAMMA RAYS A THESIS SUBMITTED TO THE UNIVERSITY OF NORTH BENGAL IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY IN PHYSICS BY SABYASACHI RAY SUPERVISOR DR. RAJAT K. DEY [DEPT. OF PHYSICS] UNIVERSITY OF NORTH BENGAL September 2023

i DECLARATION I, Sabyasachi Ray, declare that this thesis titled, "STUDYING THE ORIGIN OF COS- MIC RAYS THROUGH TeV-PeV ENERGY NEUTRINOS AND GAMMA RAYS" has been prepared by me under the guidance of Dr. Rajat K. Dey, Associate Professor of Department of Physics, University of North Bengal. No part of this thesis has formed the basis for the award of any degree or fellowship previously. (Sabyasachi Ray) Department of Physics, University of North Bengal, P.O.- North Bengal University, District- Darjeeling, Pin Code- 734013 West Bengal, India. Date:

ii Dedicated to my parents...

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DEDICATED TO MY PARENTS

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with me helped me a lot throughout the time.

I am indebted to my parents for their endless love, encouragement, and belief in my abilities. Their unwavering support and sacrifices have been the driving force behind my achievements. I am eternally grateful for their continuous motivation and understanding.

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In conclusion, I express my deepest gratitude to all those who have supported and believed in me throughout this thesis. Your guidance, encouragement, and unwavering support have been instrumental in my journey towards completing this milestone. I am forever thankful for your presence in my life.

ABSTRACT

The origin of cosmic rays is regarded as one of the fundamental open questions of modern physics. To inquire more clearly the astrophysical environments and the viable mechanisms which sustain the huge power for their acceleration, it is imperative to investigate the fluxes of multi-messenger particles reaching the Earth. In this context, the discovery of diffuse flux of astrophysical neutrinos in 2013 by IceCube added an important class of multi-messenger particles into the field. The aim of the work performed by the author (in collaboration with a few others) in this thesis is basically related to a theoretical estimation of the TeV−PeV energy fluxes of these neutrinos and/or accompanying gamma rays from some plausible astrophysical sources (point-like and diffuse sources). The main objectives of the thesis are

[i] to probe the origin of cosmic rays through TeV−PeV energy multi-messengers namely neutrinos and gamma rays,

[ii] to estimate theoretically the TeV−PeV energy neutrino and/or gamma-ray fluxes at Earth primarily from the aftermath processes of the acceleration era of VHE−UHE protons and nuclei or electrons on the ambient matter and/or radiative background at the source environment or ISM,

[iii] to apply the above methodology to estimate diffuse fluxes of TeV−PeV energy astrophysical neutrinos coming from all directions in the sky contributed by three source classes: (i) extragalactic milli-second pulsars; (ii) AGN and (iii) an extended source - Galactic center. Moreover, we estimate astrophysical neutrino fluxes from some predefined point-like galactic source classes by IceCube: (i) pulsars and nebulae, and (ii) magnetars. We also estimated the TeV−PeV energy flux of gamma rays produced concurrently with neutrinos in those astrophysical sources,

[iv] to understand the astrophysical origin of IceCube (diffuse neutrino flux) and also the Antarctic Muon and Neutrino Detector Array - AMANDA-II (directed neutrino flux) detected TeV−PeV energy neutrinos by analyzing the theoretically predicted fluxes of neutrinos. This study is closely linked with the origin of cosmic rays. The thesis emphasizes to enlighten this area primarily,

and

[v] to understand the observed data on gamma-ray fluxes obtained from experiments *viz.* High Altitude Water Cherenkov (HAWC) and LHAASO by analyzing the predicted fluxes of accompanying gamma rays.

The **first chapter** of this thesis has given an overview of the multi-messenger astronomy, aimed at exploring the cosmos by blending two important windows of astrophysics with the use of cosmic messengers: TeV−PeV energy neutrinos and gamma rays.

A synopsis of the present status of the gamma-ray and neutrino astronomy from both theoretical and experimental standpoints concerning cosmic-ray origin is given in the **second chapter**. In this context, it also reviews the theoretical basis of adopted particle acceleration models and photon-splitting process, a QED process that takes place in presence of strong magnetic fields.

The **third to sixth chapters** are focused on the author's original research works on the origin of cosmic rays through the study of TeV−PeV energy neutrinos and gamma rays.

The **third chapter** is divided into two main parts: in **part A**, an estimation of the fluxes of TeV neutrinos and gamma rays to be observed at Earth from pulsars polar caps via interaction of polar cap accelerated protons with radiative background is presented; **part B** deals with the estimation of PeV neutrino and gamma-ray fluxes from magnetar polar caps, considering that protons are accelerated in polar cap regions, and interact with background photon fields (ultraviolet A and B type soft photons). In this context, the observational situation of neutrino and gamma ray detections by the current and possible future experiments are discussed.

The **fourth chapter** goes into detail about the methodology of revised estimation of the diffuse flux of PeV neutrinos produced in the accretion disk region of active galactic nuclei (AGN) by centrifugally accelerated protons on the soft photon targets based on the latest cosmological framework with a view to predicting the observed diffuse flux of PeV neutrinos by IceCube. The diffuse PeV gamma rays produced together with neutrinos, and their possibilities to be detected at Earth are also discussed.

The **fifth chapter** describes the hadronic emission scenario in the extended source Sagittarius $A^\star$ with energies ~ 100 PeV or more, followed by an estimation of the diffuse

fluxes of PeV neutrinos and gamma rays produced via cosmic rays-gas/ISM (pp) interactions. The chapter ends with a concise discussion on the detection feasibility of the predicted low fluxes of galactic PeV neutrinos and gamma rays at Earth by the current and future generations of neutrino and gamma-ray observatories.

Hadronic scenarios are widely accepted for the production of high-energy neutrinos. Most of the models proposed in earlier studies took $p\gamma$ and/or pp interactions for the production of UHE neutrinos in different sources. But, the **sixth chapter** focuses on the estimation of diffuse flux of PeV neutrinos contributed by the process of purely leptonic origin, particularly, via the e^-e^+ interaction in new-born milli second pulsars in the universe at redshifts in the range $0.002 - 5$. The chapter also derives the high-energy diffuse gamma-ray flux for a relevant $e^-\gamma_{low}$ interaction, in softer radiation field zones in pulsar's environment. The chapter ends with a discussion on the possibility of leptonic originated diffuse neutrinos to be detected by IceCube.

A summary of the presented research work with a brief discussion is presented finally in **seventh chapter**.

The results reported in this thesis have been published in peer-reviewed journal papers, and in proceedings/book chapters. A list of these papers is provided in the **Preface** of the thesis.

Preface

The origin of cosmic rays remains one of the greatest challenges in modern physics even after more than 110 years of their discovery. They span an enormous range of energy from about 10^{10} eV to beyond 10^{20} eV. Above 10^{15} eV, and up to $\sim 10^{19}$ eV, there are three spectral breaks/features, namely the knee or the first knee, the 2nd knee and the ankle in the observed energy spectrum of cosmic rays. Beyond this, the spectrum exhibits one more interesting feature at around $\gtrsim 4 \times 10^{19}$ eV that can be explained with the theoretical GZK cut-off. The proper explanation of all of these features is supposed to be a corner stone in understanding the origin of cosmic rays.

The interaction of energetic cosmic rays with ambient matter or radiative fields in the vicinity of their accelerators or in ISM is believed to produce VHE−UHE neutrinos and gamma rays. In principle, the leptonic mechanisms can generally produce gamma rays while high-energy neutrinos are the indicator for hadronic mechanisms. Moreover, the unique propagation feature of neutrinos through dense environments or ISM thus make them as a unique tracer of the sources of cosmic rays. Hence, probing the origin of cosmic rays can be realized through TeV−PeV energy multi-messengers namely neutrinos and gamma rays.

In 2013, IceCube reported the first observation of a diffuse flux of TeV−PeV energy astrophysical neutrinos of extragalactic origin. Later in 2018, IceCube also reported the first clear evidence of association of astrophysical neutrinos (*e.g.* IceCube 170922- A neutrino event) with a cosmic-ray source - the flaring blazar TXS 0506+056. However, the responsible astrophysical accelerators for the production of the detected HESE (high energy starting-events) neutrino events of IceCube still remain unexplained. This unsettled issue requires some additional studies, a part of which has been carried out during my research. The main goal of the thesis is to understand the astrophysical origin of IceCube (diffuse neutrino flux) and also the Antarctic Muon and Neutrino Detector Array - AMANDA-II (directed neutrino flux) detected TeV−PeV energy neutrinos by analyzing our theoretically predicted fluxes of neutrinos. Additionally, the suggested analysis of the predicted gamma-ray fluxes are utilized to understand the observed data on gamma-ray fluxes obtained from experiments *viz.* HAWC and LHAASO.

In order to contextualize the results obtained on the theoretical estimation of gamma-ray and neutrino fluxes from some plausible astrophysical sources (point-like and diffuse sources) during my research work, the thesis is organized as follows:

Chapter 1 gives an overview on multi-messenger astronomy, aimed at exploring the cosmos by blending two important windows of astrophysics with the use of cosmic messengers: TeV−PeV energy neutrinos and gamma rays. The chapter introduces cosmic rays and their connection to neutrinos and gamma rays, lists potential galactic/extragalactic astrophysical accelerators, and how they can produce these cosmic messengers.

Chapter 2 reviews the current status of gamma-ray and neutrino astronomy from both theoretical and experimental standpoints concerning cosmic-ray origin. In this context, it also reviews the theoretical basis of adopted particle acceleration models and photon-splitting process, a QED process that takes place in presence of strong magnetic fields.

In the following *four* chapters author's original research (in collaboration with few others) on cosmic-ray origin through the study of TeV−PeV energy neutrinos and gamma rays is discussed.

Chapter 3 is divided into two main parts: in part A, an estimation of the fluxes of TeV neutrinos and gamma rays to be observed at Earth from pulsars polar caps via interaction of polar cap accelerated protons with radiative background is presented; part B deals with the estimation of PeV neutrino and gamma-ray fluxes from magnetar polar caps, considering that protons are accelerated in polar cap regions, and interact with background photon fields (ultraviolet A and B photons). In this context, the observational situation of neutrino and gamma ray detections by the current and possible future experiments are discussed.

Chapter 4 goes into detail about the methodology of revised estimation of the diffuse flux of PeV neutrinos produced in the accretion disk region of AGN by centrifugally accelerated protons on the soft photon targets based on the latest cosmological framework with a view to predicting the observed diffuse flux of PeV neutrinos by IceCube. The diffuse PeV gamma rays produced together with neutrinos, and their possibilities to be detected at Earth are also discussed.

Chapter 5 describes the hadronic emission scenario in the extended source Sagittarius $A^\star$ with energies $\sim$ 100 PeV or more, followed by an estimation of the diffuse fluxes

of PeV neutrinos and gamma rays produced via cosmic rays-gas/ISM (pp) interactions. The chapter ends with a concise discussion on the detection feasibility of the predicted low fluxes of galactic PeV neutrinos and gamma rays at Earth by the current and future generations of neutrino and gamma-ray observatories.

Chapter-6 Hadronic scenarios are widely accepted for the production of high-energy neutrinos. Most of the models proposed in earlier studies took $p\gamma$ and/or pp interactions for the production of UHE neutrinos in different sources. But, this chapter focuses on the estimation of diffuse flux of PeV neutrinos contributed by the process of purely leptonic origin, particularly, via the e^-e^+ interaction in new-born millisecond pulsars in the universe at redshifts in the range $0.002 - 5$. The chapter also derives the high-energy diffuse gamma-ray flux for a relevant $e^-\gamma_{low}$ interaction, in softer radiation field zones in pulsar's environment. The chapter ends with a discussion on the possibility of leptonic originated diffuse neutrinos to be detected by IceCube.

Chapter 7 gives a summary of the presented research work with a brief discussion.

The thesis is based on the results presented in **Chapter 3** to **Chapter 6**. Major results of it have already been published in the following peer-reviewed journals/proceedings, some of which, are attached at the end of the thesis.

SCI Journals:

• Authors: Rajat K. Dey, **Sabyasachi Ray** and Sandip Dam
Title: *Searching for PeV neutrinos from photomeson interactions in magnetars.*
Journal: *Europhys. Letts.*, **115** 69002 (2016). [Attached at the end]

• Authors: Rajat K. Dey, Animesh Basak, **Sabyasachi Ray** and Tamal Sarkar
Title: *Newly born extragalactic millisecond pulsars as efficient emitters of PeV neutrinos.*
Journal: *Braz. J. Phys.*, **51(5)** 1406 (2021).

• Authors: Rajat K. Dey, **Sabyasachi Ray** and Animesh Basak
Title: *Diffuse flux of PeV neutrinos from centrifugally accelerated protons in active galactic nuclei.*
Journal: *Europhys. Letts.* **136** 69001 (2021). [Attached at the end]

• Authors: **Sabyasachi Ray** and Rajat K. Dey
Title: *Sgr A* as a plausible source candidate for PeV neutrinos.*
Journal: *Communicated for publication in 2023.*

• Authors: Rajat K. Dey, **Sabyasachi Ray** and Sandip Dam
Title: *Searching for correlations of geomagnetic activities with high-energy EAS muons.*
Journal: *Euro. Phys. J. Plus*, **135(6)** 1 (2020) [Not included in the thesis].

• Authors: Rajat K. Dey, Sandip Dam and **Sabyasachi Ray**, Animesh Basak and Pradip Chattopadhyay
Title: *Determination of the mass and energy of primary cosmic rays above 100 TeV*
Journal: *Indian J. Phys.*, **92(11)** 1357 (2018) [Not included in the thesis].
• Authors: Rajat K. Dey, Sandip Dam and **Sabyasachi Ray**
Title: *Imprint of the atmospheric attenuation process on electron distribution in EAS.*
Journal: *Indian J. Phys.*, **91(4)** 359 (2017) [Not included in the thesis].

International/National Conference Proceedings:
• Authors: Rajat K. Dey [talk published in a proceedings]
Title: *PeV Neutrinos from Local Magnetars*
Proceedings:*XXII DAE High Energy Physics Symposium, Springer Proc. in Phys.* **203** 1 (2018); https://doi.org/10.1007/978-3-319-73171-1_32.
• Authors: Rajat K. Dey, Animesh Basak, **Sabyasachi Ray** and Tamal Sarkar [poster published in a proceedings]
Title: *PeV neutrinos from centrifugally accelerated electrons in extragalactic new born pulsars.*
Proceedings: *DAE Symp. on Nucl. Phys.* **65** 506 (2021). [Attached at the end]
• Authors: Animesh Basak, **Sabyasachi Ray** and Rajat K. Dey [poster published in a proceedings]
Title: *Extraterrestrial diffuse flux of PeV scale neutrinos from accretion disk regions of active galactic nuclei.*
Proceedings: *DAE Symp. on Nucl. Phys.* **65** 508 (2021).
• Authors: **Sabyasachi Ray**, Rajat K. Dey and Tamal Sarkar [poster published in a proceedings]
Title: *Sgr A⋆ as a potential source of galactic PeV neutrinos.* Proceedings: *DAE Symp. on Nucl. Phys.* **66** 822 (2022). [Attached at the end]

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List of Abbreviations

GeV	**G**iga **e**lectron **V**olt
TeV	**T**era **e**lectron **V**olt
PeV	**P**eta **e**lectron **V**olt
UHE	**U**ltra **H**igh **E**nergy
SNR	**S**uper **N**ova **R**emnant
GRB	**G**amma **R**ay **B**urst
AGN	**A**ctive **G**alactic **N**uclei
LLCD	**L**angmuir **L**andau **C**entrifugal **D**rive
MSP	**M**illi **S**econd **P**ulsar
VHE	**V**ery **H**igh **E**nergy
PWN	**P**ulsar **W**ind **N**ebulae
IACT	**I**maging **A**tmospheric **C**herenkov **T**elescope
H.E.S.S.	**H**igh **E**nergy **S**tereoscopic **S**ystem
MAGIC	**M**ajor **A**tmospheric **G**amma **I**maging **C**herenkov **T**elescopes
VERITAS	**V**ery **E**nergetic **R**adiation **I**maging **T**elescope **A**rray **S**ystem
HAWC	**H**igh **A**ltitude **W**ater **C**herenkov Experiment
Fermi- LAT	**F**ermi- **L**arge **A**rea **T**elescope
DOM	**D**igita **O**ptical **M**odules
PMT	**P**hoto **M**ultiplier **T**ube
CTA	**C**herenkov **T**elescope **A**rray
LSD	**L**iquid **S**cintillationtands **D**etector
LVD	**L**arge **V**olume **D**etector
QED	**Q**uantum **E**lectro **D**ynamics
GJ	**G**oldreich- **J**ulian
CANGAROO	**C**ollaboration between **A**ustralia and **N**ippon for a **GA**mma **R**ay **O**bservatory in the **O**utback
HEGRA	**H**igh-**E**nergy-**G**amma-**R**ay **A**stronomy
EGRET	**E**nergetic **G**amma **R**ay **E**xperiment **T**elescope
NS	**N**eutron **S**tar
CR	**C**osmic **R**ay
SB	**S**tephan- **B**oltzmann

AMANDA	**A**ntarctic **M**uon **A**nd **N**eutrino **D**etector **A**rray
ICS	**I**nverse **C**ompton **S**cattering
CDFN	**C**handra **D**eep **F**ield-**N**orth
CDFS	**C**handra **D**eep **F**ield-**S**outh
LF	**L**uminosity **f**unction
XLF	**X**-ray **L**uminosity **f**unction
CDM	**C**old **d**ark **m**atter
FRW	**F**riedmann-**R**obertson-**W**alker
CMB	**C**osmic **M**icrowave **B**ackground
BBW	**b**reakdown of the **b**ead on the **w**ire approximation
AXP	**A**nomalous **X**-ray **p**ulsar

Physical Constants

Speed of Light	$c_0 = 2.9979 \times 10^{10}\,\mathrm{cm\,s^{-1}}$
Newton's gravitational constant	$G = 6.6743 \times 10^{-8}\,\mathrm{cm^3\,g^{-1}\,s^{-2}}$
Planck's constant	$h = 6.6261 \times 10^{-27}\,\mathrm{cm^2\,g\,s^{-1}}$
	$= 4.1357 \times 10^{-15}\,\mathrm{eV\,s}$
reduced Planck's constant	$\hbar = 1.0546 \times 10^{-27}\,\mathrm{cm^2\,g\,s^{-1}}$
	$= 6.5821 \times 10^{-16}\,\mathrm{eV\,s}$
Boltzmann's constant	$K = 1.3807 \times 10^{-16}\,\mathrm{cm^2\,g\,s^{-2}\,K^{-1}}$
	$= 8.6173 \times 10^{-5}\,\mathrm{eV\,K^{-1}}$
Stefan-Boltzmann constant	$\sigma = 5.6704 \times 10^{-5}\,\mathrm{g\,s^{-3}\,K^{-4}}$
electron charge	$e = 4.8032 \times 10^{-10}\,\mathrm{cm^{3/2}\,g^{1/2}\,s^{-1}}$
electron mass	$m_e = 9.1094 \times 10^{-28}\,\mathrm{g}$
	$= 0.511\,\mathrm{MeV/c^2}$
proton mass	$m_p = 1.6726 \times 10^{-24}\,\mathrm{g}$
	$= 938.272\,\mathrm{MeV/c^2}$
neutron mass	$m_n = 1.6749 \times 10^{-24}\,\mathrm{g}$
	$= 939.563\,\mathrm{MeV/c^2}$
atomic mass unit	$u = 1.6605 \times 10^{-24}\,\mathrm{g}$
	$= 931.494\,\mathrm{MeV/c^2}$
erg (unit of energy)	$erg = 1\,\mathrm{cm^2\,g\,s^{-2}}$
	$= 6.2415 \times 10^{11}\,\mathrm{eV}$

Astronomical Constants

Quantity	Symbol	Value (cgs units)
Solar mass	$M_\odot$	1.989×10^{33} g
Solar radius	$R_\odot$	6.955×10^{10} cm
Solar luminosity	$L_\odot$	$3.839 \times 10^{33} ergs^{-1}$
astronomical unit	AU	1.496×10^{13} cm
parsec	pc	3.086×10^{18} cm
light-year	ly	9.461×10^{17} cm
year	yr	3.156×10^{7} s