Chapter 1

Introduction

During 1964 to 1967, some remarkable discoveries, namely the observations of the cosmic microwave background radiation (CMBR), the first radio pulsar, or the gamma-ray bursts led to realize about the feasibility of several new windows other than usual visible wavelength to observe the cosmos. In the same way, a galactic source LHAASO J1908+0621 has been explained recently as a cosmic-ray PeVatron with the observations of the same photon messengers carrying TeV−PeV energies from the source by Large High Altitude Air Shower Observatory (LHAASO) experiment [1].

For exploring the cosmos, several new windows with the use of other messengers, such as the TeV−PeV energy neutrinos and gravitational waves have come up in the last decade. The discovery of the TeV−PeV energy astrophysical neutrinos by the IceCube experiment has given an evidence to use these messengers for probing the origin of cosmic rays [2]. A convincing evidence of neutrino observations by IceCube correlated to an extra-galactic source blazar TXS 0506+056 in 2018 established a strong foundation for the field [3]. Furthermore, the gravitational waves detected by Laser Interferometer Gravitational-Wave Observatory (LIGO) experiment [4] has opened a complete new window to detect massive objects residing at much distant places from Earth.

Neutrino and gamma-ray astronomy in the TeV−PeV scale has usually been linked with very-high energy (VHE) to ultra-high energy (UHE) cosmic rays. Since revealing the origin of cosmic rays is the prime objective of the thesis, we discuss them first in the next Section 1.1. In Section 1.2, we briefly present an overview of the gamma-ray and neutrino astronomy in the TeV−PeV scale. In Section 1.3, the objectives of the thesis are briefly described.

1.1 Cosmic rays

Cosmic rays are highly relativistic particles which constantly impinging the Earth atmosphere have been discovered more than 110 years ago by Victor Hess during his balloon flights mission [5]. Over this long time span, we have learned a great deal about the energetic radiation concerning its nature, origin, acceleration and propagation. Observations of growing ionization level during several balloon ascends by Hess, were mostly caused by relativistic protons and atomic nuclei. The principal components in its composition are protons, and Helium nuclei but there are also relatively lesser proportions of heavier nuclei, and an insignificant electromagnetic component $-$ gamma rays and electrons as well [6]. The cosmic-ray physics encompasses a wide range in energy and intensity, and follows almost uniform power laws and dependencies at various orders of magnitude. Such a feature of cosmic rays gives a clue that some common principles are responsible for production and acceleration mechanisms of cosmic-ray particles. At energies beyond few tens of PeV, however, their sources and exact mechanisms of acceleration remain a great mystery in physics of astroparticles.

1.1.1 Energy spectrum of cosmic rays

The spectrum of cosmic rays reaching the Earth, shown in Fig. 1.1 cover a wide range of energy. Their differential energy spectrum follows a simple form of a steeply falling power-law with a spectral index γ for energies beyond the solar modulated one as [6]

$$\frac{dN}{dE} \propto E^{-\gamma} \tag{1.1}$$

γ would experience slight variations at some specific energies casting some interesting spectral features into the spectrum. The features in the spectrum are a field of active research and supposed to be linked with the origin of cosmic rays [7, 8]. The spectral index γ with a value 2.7 can describe the spectrum nicely in the energy region: $10^{10} - 3 \times 10^{15}$ eV *i.e.* up to the so called knee of the spectrum. Just beyond the knee at 3×10^{15} eV, the spectrum becomes steeper with a value ≈ 3.1. The steepening of the spectrum is supposed to hint that galactic cosmic rays (mostly originating from supernovae) have attained their maximum energy for lighter components of protons and helium nuclei [6]. In the last decade, the KASCADE-Grande experimental data indicated another steepening, called the second knee or iron knee at about $(2-8) \times 10^{16}$ eV [9]. This feature is linked with the maximum energy attainable by heavier nuclei from the galactic cosmic-ray sources beyond which cosmic-ray nuclei leave the source with no further acceleration.

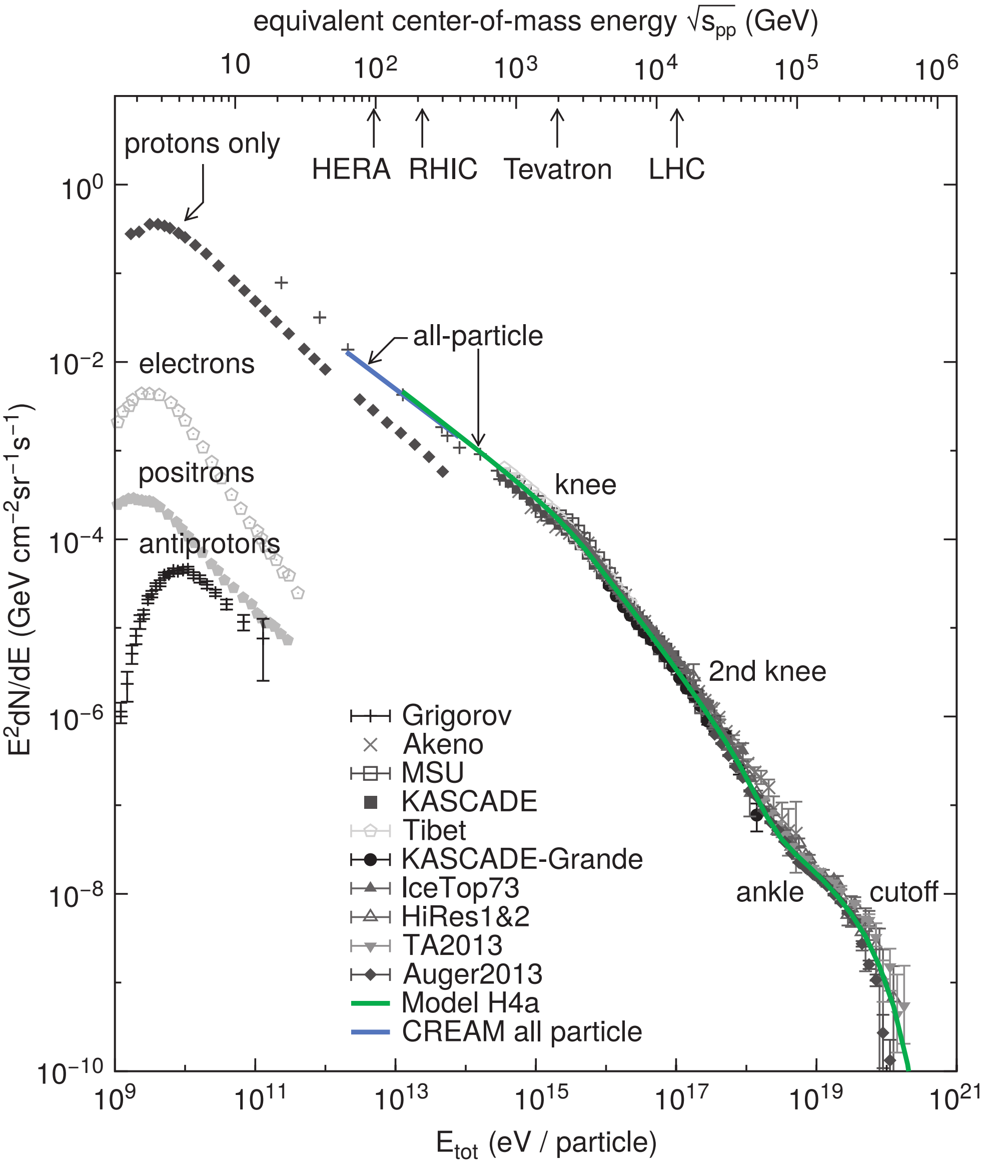

FIGURE 1.1: All-particle spectrum of cosmic rays, spanning 11 orders of magnitude in energy. The flux has been scaled by E^2 in order to exhibit the steeply falling features of the spectrum [10].

Beyond 10^{18} eV, a new feature (spectral hardening), called the ankle, is detected. This feature is claimed to be associated with the extragalactic origin of cosmic rays [8]. Near the end of the spectrum, a strong suppression (known as the Greisen-Zatsepin-Kuzmin (GZK) suppression) of the cosmic-ray intensity due to their interactions with CMBR photons occurs at around $10^{19.5}$ eV in the observed all-particle energy spectrum; see Fig. 1.1 [11,12].

1.1.2 Origin of cosmic rays

The low energy cosmic rays up to energies $\sim 10^{10} - 10^{11}$ eV of the energy spectrum are known to be originated from nearby normal stars including the Sun [13]. The effects of the heliospheric and then the geomagnetic fields spiral them into the Earth's magnetic poles. Finally before reaching the ground, these charged particles produce *auroras* in the sky via ionization/excitation with the atmospheric atoms.

Generally, cosmic rays until $\sim 10^{15}$ eV of the energy spectrum are believed to be of galactic origin. A combination of the diffusive shock acceleration in supernova remnants (SNRs) with the most likely propagation in the galaxy is a well-accepted explanation for acceleration of these galactic cosmic rays. The diffusive shock acceleration (DSA) in SNRs can explain a power-law, $\propto E^{-2}$ of the cosmic-ray flux emitted by the source but the power-law obtained from data at Earth follows a $\sim E^{-2.7}$ dependence of the observed flux [14]. Such a deviation of the observed spectral index can be interpreted by the leaky box model for the propagation of cosmic rays in the galactic and intergalactic magnetic fields [15].

Beyond 10^{15} eV, and up to $\sim 10^{18.5}$ eV, there are three spectral breaks (namely the knee or the first knee, the 2nd knee and the ankle) in the observed energy spectrum of cosmic rays. The steepening in the slope of the cosmic-ray spectrum just above the knee is found consistent with the maximum energy reached by cosmic-ray protons in the accelerator i.e. in SNRs. A numerous number of EAS experiments associated the knee energy ($E_{knee} \approx 3 \times 10^{15}$ eV) of the spectrum with some sort of cessation effect of the lighter elements in the cosmic-ray composition [16]. The second knee is visible at around $\approx 8 \times 10^{16}$ eV in the spectrum, which is nearly equal to $26 \times E_{knee}$. This would obviously appear as an outcome of the acceleration of the heaviest nuclei $-$ iron ($Z = 26$) in SNRs [9]. Thus, the spectrum in the energy range $3 \times 10^{15} \lesssim E \lesssim 8 \times 10^{16}$ eV can be explained as the superposition of various cut-offs corresponding to the spectra of different elements between proton and iron. Moreover, it gives evidence in favour of SNR origin of galactic cosmic rays up to an energy $\sim 10^{17}$ eV in the spectrum. Other probable galactic sources which may supply a small percentage of cosmic rays could be pulsars, pulsar wind nebulae (PWN), magnetars, galactic center (GC) and colliding wind binaries [17]. The SNRs with stronger magnetic fields in the shock fronts may be efficient to accelerate cosmic rays even up to $\sim 10^{18}$ eV with the working of some nonlinear diffusive shock acceleration (DSA) mechanism [18,19].

Another spectral break (or hardening) occurs at about 3×10^{18} eV, known as the ankle of the energy spectrum, where the power-law for the cosmic-ray flux flattens back to $\sim E^{-2.7}$ manner [20]. This spectral feature is believed to be linked with the sources of extragalactic cosmic rays. Beyond the ankle, the galactic magnetic field is unable to restrain the Larmour radii of cosmic-ray components within the size of the accelerating region [21]. The anisotropies found in the Pierre Auger Observatory (PAO) cosmic-ray data can only be explained with the cosmic rays coming from bright extragalactic sources with energies much above 10^{18} eV [22]. The possible extragalactic sources which may be capable to accelerate charged particles from neutron stars (NS), white dwarfs, merging galaxy clusters, gamma-ray bursts (GRB), active galactic nuclei (AGN), starburst galaxies etc.

The all-particle cosmic-ray energy spectrum at around $\gtrsim 4 \times 10^{19}$ eV can be explained with the theoretical GZK cut-off [12,23]. The interaction of UHE protons with the CMBR photons produces the cut-off which restrict these UHE protons to travel from arbitrarily large distances.

The viable resolution of the open question of the origin of VHE$-$UHE cosmic rays demands a precise measurements of the main facets of cosmic-ray observations; namely the energy spectrum, composition and anisotropy. The multi-messenger interface dealing with the measurements of TeV$-$PeV energy neutrino and gamma-ray (photons) fluxes came up as a complementary front towards the resolution of the enigma of the origin of cosmic rays.

Until now, we have given an overview of one of the fundamental issues related to cosmic-ray origins, that is, where from they come?. This question is intimately linked with the acceleration processes of cosmic rays by which they acquire such an enormous energy. The acceleration mechanisms relevant to our research works presented in the thesis are introduced and reviewed in Chapter 2 (Section 2.3).

1.2 Gamma-ray and neutrino astronomy

Cosmic-ray protons and nuclei can interact with galactic and extragalactic magnetic fields which do not allow them for directly pointing to their accelerator sites from Earth. In addition, the energy loss processes (their collisions at the highest energies $E > 5 \times 10^{19}$ eV with CMBR) during their propagation over cosmic distances rule out the possibility of probing the deepest interiors of their accelerators [24].

The inherent processes occurring in astrophysical sources result into the production of charged cosmic-ray particles (such as protons, other nuclei and electrons), which then turn into the production of gamma rays and neutrinos. Thus, produced gamma rays and neutrinos, which traveling in straight lines, can provide some gateway to the origin of VHE−UHE cosmic rays in the universe. These probing particles are produced via two principal channels [25]: (i) leptonic processes and (ii) hadronic processes. Leptonic processes usually exploit $e^{\pm}$ as energetic projectiles while cosmic-ray protons, helium nuclei etc. act as projectiles in hadronic processes.

The possible leptonic processes from which gamma rays emerge are identified into [25]: (i) Bremsstrahlung radiation, (ii) Synchrotron radiation and (iii) inverse Compton scattering (ICS) . If charge particles (dominant for electrons) are decelerated by the electric field of target atoms, in virtue of that gamma-ray photons are emitted, and the process is given in Eq. 1.2. When electrons interact with local magnetic fields, they are accelerated radially, and produce gamma-ray photons hugely from electrons, and the process is given in Eq. 1.3. The ICS is predominant when ultra-relativistic electrons scatter cold photons, as a result low energy photons gain energy from electrons to become high energy gamma-ray photons, is given through Eq. 1.4 [26]. It should be however mentioned that Bremsstrahlung/Synchrotron processes are dominating leptonic processes to produce gamma rays, particularly in the low energy regime.

$$e^{\pm} + nucleus \longrightarrow nucleus + e^{\pm} + \gamma \tag{1.2}$$

$$e^{\pm} + B - field \longrightarrow B - field + e^{\pm} + \gamma \tag{1.3}$$

$$e^{\pm}_{high} + \gamma_{low} \rightarrow e^{\pm}_{low} + \gamma_{high} \tag{1.4}$$

In some astrophysical environments, if electrons are pumped to UHEs and also could avoid energy diminution processes, then a very negligible fraction of them may produce neutrinos via the lepton-hadron and the lepton-lepton channels [27,28].

$$e^{-} + p \rightarrow n + \nu_e \tag{1.5}$$

$$e^- + e^+ \rightarrow \nu_l + \tilde{\nu}_l; (l = e, \mu, \tau) \tag{1.6}$$

The hadronic cosmic rays (mostly protons) are accelerated in different astrophysical sites in extreme conditions. Accelerated protons will collide inelastically with cold hadronic matters (mainly protons) and background radiations via proton−proton and proton−photon hadronic channels. The cold protons are abundant in regions surrounding to the accelerators, interstellar matter (ISM) etc. The simplest hadronic process is the following:

$$p + p \rightarrow p + p + N[\pi^0, \pi^+, \pi^-] \tag{1.7}$$

where N accounts the pion multiplicity.

Pions are also produced from the photo-hadronic process via Δ^+ resonance production [29].

$$p + \gamma \rightarrow \Delta^+ \rightarrow \begin{cases} p + \pi^{\mathrm{o}} \\ n + \pi^+ \rightarrow n + e^+ + \nu_{\mathrm{e}} + \nu_\mu + \bar{\nu_\mu} \end{cases} \tag{1.8}$$

For pion decay schemes, each neutral pion produces two gamma-ray photons while a charged pion decays into three neutrinos. These decays proceed as:

$$\pi^0 \rightarrow \gamma + \gamma \tag{1.9}$$

$$\pi^\pm \rightarrow \mu^\pm + \nu_\mu(\overline{\nu_\mu}) \rightarrow e^\pm + \nu_e(\overline{\nu_e} + \overline{\nu_\mu}(\nu_\mu) + \nu_\mu(\overline{\nu_\mu}) \tag{1.10}$$

Thus far, the most energetic cosmic gamma rays have been unambiguously detected at Earth with energy $\sim$ 100 TeV. High energy gamma-ray photons go through strong absorption en route due to pair production while propagating in the radiative background (or ambient radiation fields) of the Milky Way. The diffuse extragalactic background light (EBL) and the uniformly distributed CMBR through the intergalactic/galactic space also prevent very high energy gamma rays of energies, $E_\gamma \gtrsim$ 100 TeV to travel extragalactic distances owing to their attenuation. On the other hand, since gamma rays are produced via both the hadronic and leptonic processes, thus it becomes very formidable to resolve the issue of the origin of cosmic rays solely from the gamma-ray observations.

As the hadronic processes are indispensable to produce high-energy neutrinos, their observation seems very meaningful for probing the origin of cosmic rays. As neutrinos are weakly interacting, they do not attenuate like photons during their propagation, and thus reaching Earth in straight lines from inner regions of extragalactic sources. Such an inherent property of neutrinos make them ideal messengers to be used for neutrino astronomy, particularly in the VHE−UHE range [30]. However, they are extremely difficult to detect as they can cross large amounts of mass without interacting. Thus huge detecting systems need to be equipped in neutrino observatories in challenging environments to collect a statistically significant number of galactic/extragalactic neutrinos [24].

It has been learned from the overview of the field - 'Gamma-ray and neutrino astronomy', that a number of galactic gamma-ray sources are discovered at energies around $E_\gamma \lesssim 100$ TeV, but no galactic neutrino sources of $E_\nu \sim 100$ TeV have been detected yet [31–36]. Such findings from the observational front indicate that galactic sources might have fulfilled required conditions for producing TeV gamma rays via leptonic channels [34–36].

1.3 Objectives of the thesis

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 [37]) neutrino events of IceCube still remain unexplained. This unsettled issue requires some additional studies, a part of which has been carried out during our research work. The aim of the research work envisaged during my Ph.D. tenure is to estimate theoretically the fluxes of TeV$-$PeV neutrinos, and accompanying gamma rays reaching Earth, produced in some plausible astrophysical sources (point-like and diffuse sources) for exploring the origin of IceCube detected neutrinos, thereby probing the origin of cosmic rays.

In the context of the aim of the research undertaken, the main objectives of the thesis are

- To probe the origin of cosmic rays through TeV$-$PeV energy multi-messengers namely neutrinos and gamma rays.

- 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.

• 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 (MSP); (ii) AGN and (iii) an extended source - GC. 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.

• 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.

• 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.

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