Chapter 1

Cosmic rays and extensive air showers

1.1 Introduction

Cosmic rays (CRs) are the highly energetic charged particles which stream into our atmosphere from outer space continuously. Discharging effect of well insulated electroscopes or other electrically charged vessels or ionization of gases contained within a closed vessel, were the preliminary evidences for the existence of CRs during the first few decades of the 20th century. In the last 30–40 years, we have gained substantial knowledge on CRs due to the availability of sophisticated technology and continuous efforts of many international research groups. However, there are still many unresolved issues, and divergence in opinions. The important ones are "What are their origin?" and "How do they get enormous energy?".

1.1.1 A brief historical overview

In the history of CR research, it was believed that the radioactive elements in the Earth could cause the radiation. It was known that radiation from radioactive elements were absorbed in the air and their intensity decreases with height from the Earth surface. Theodor Wulf, a German Jesuit priest and physicist, observed that ionization reduced from 6×10^6 ions m^{-3} to 3.5×10^6 ions m^{-3} as he ascended the Eiffel Tower in 1910, a height of 330 m, where the intensity of the radiation should have been negligible [1]. This experiment made Theodor Wulf to believe that it's not the Earth as a source of radioactivity but the cosmos from where the extraterrestrial radiations fall down on the atmosphere. In 1912, Victor Hess discovered CRs by measuring ionizing effect of this radiation during his balloon ascents [2]. He observed that at an altitude of 5 km the ionization rate was several times compared to sea level. This was Clay [3], who established that CRs are made up of relativistic charged particles. About 10 years later in 1938, P. Auger and his team were able to show that CRs contain charged particles with different mass numbers and they interact with air nuclei in the atmosphere, and generate a cascade of secondary particles. The cascade of secondary particles, called the extensive air showers were also detected in subsequent years with the employment of simple radiation detectors those were operated in coincidence. This was known to be the beginning of a new detection technique to investigate CRs at TeV - PeV energies or even beyond. Nowadays, the giant air shower arrays are dedicated for the detection and measurement of EASs induced by very high-energy to ultra-high-energy (UHE) CRs.

1.1.2 The energy spectrum of primary cosmic rays

Since the discovery of CRs, the studies over the CR energy spectrum have been carried out by many researchers. Studies on CR energy spectrum open up many areas of research in this field, such as the origin of CRs, and their acceleration, propagation, and composition. The energy spectrum of primary CRs is extended from few hundreds of MeV to approximately 10^{20} eV. Their flux decreases very rapidly with increasing energy, and it is seen that the integral flux drops from $\approx 1 particle \times m^{-2} \times s^{-1}$ at 10^{11}eV to $1 particle \times km^{-2} \times century^{-1}$ at 10^{20} eV. The energy spectrum can be described by a power law with a spectral index γ.

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

The above power law is associated with a change of the index γ from about 2.7 to 3.1 in the energy range from 10^{14}–4×10^{15} eV. A change of the spectral index actually takes place at the energy of roughly 4×10^{15} eV, known as *knee* and it was first reported by Moscow University group in 1958 [5].

Because of the decreasing CR flux, direct measurements of CRs can be done up to an energy $\approx 10^{14}$ eV by means of balloons and satellite experiments. Energies beyond this, only indirect measurements like ground-based experiments with array of detectors are being used to detect EAS generated by the CR particle during its interaction with the atmosphere.

Experimental data of Haverah Park [6], Yakutsk [7], Fly's Eye [8], and Hires [9] indicated the presence of *second knee* at an energy of roughly 4×10^{17} eV and they measured a change in the spectral index by $\Delta\gamma \approx -0.3$ arising out of the change in γ from roughly 3.0 to 3.3. However, some other experiments *viz.* AGASA [10] and Akeno [11] do not get any indication of the existence of a *second knee*. Hence, the existence of *second knee* in the energy spectrum still remains inconclusive. A soft bending and flattening effect in the energy spectrum

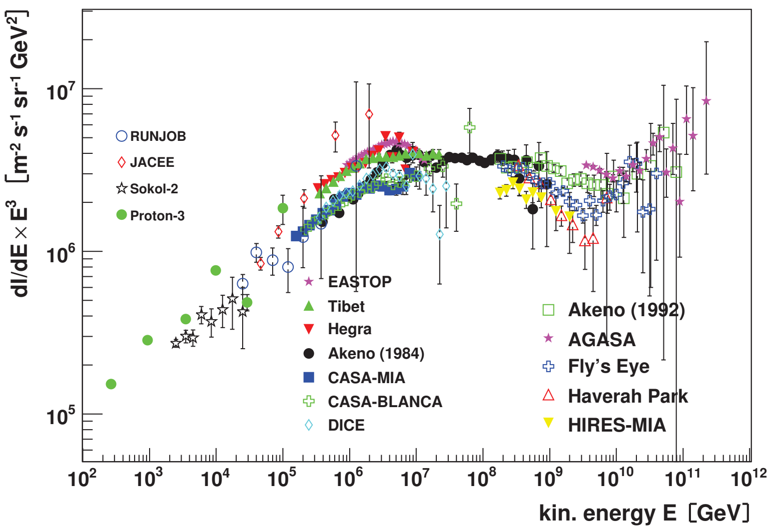

FIGURE 1.1: Energy spectrum of cosmic rays obtained from different experiments (figure is taken from [4]).

is observed at an energy roughly 5×10^{18} eV, known as the so called *ankle*, with γ roughly equals again to 2.7. The origin of this feature is believed to be due to transition from galactic to extragalactic contribution to primary CRs.

Finally, at energies above 4×10^{19} eV, the CR flux experiences a suppression [12–15], which is compatible with the Greisen-Zatsepin-Kuzmin (GZK) effect [16]. However, other possible reasons (e.g. upper limit in the energy at the source) for the suppression cannot be ruled out. According to their prediction CRs having energy more than 4×10^{19} eV interacts with cosmic microwave background radiation (CMBR) and produce pions. This process continues till energy falls below pion production threshold. The results of HiRes [17] as well as first results of

Auger [18–20] support the GZK suppression at an energy roughly to $\geq 4 \times 10^{19}$ eV.

Out of the several important features present in the CR energy spectrum the understanding of the *knee* is supposed to provide key information about the origin of galactic CRs. There are two categories of theoretical models generally deal with the origin of the *knee* [21, 22]. According to some astrophysical models, changing of the CR sources may lead to a change in the elemental composition, and their energies around the *knee* region. The second category of models assume an effect of hadronic interactions between the CR particles and the atomic nuclei in the atmosphere.

1.1.3 The mass composition of cosmic rays

According to a well established astrophysical model, the *knee* is believed to be linked with a mechanism that depends on magnetic rigidity of distributed magnetic fields in our galaxy. As a results of that one expects systematic changes in CR mass composition around the *knee* region. A physical interpretation for the *knee* mystery in terms of source and propagation properties of CRs relies on their mass composition. But due to the limited knowledge of particle interactions at energies not accessible to accelerators, a robust estimation of the CR mass composition from EAS measurements still remain somewhat uncertain.

The mass composition of CRs up to 10^{14} eV is studied by direct measurements like balloon and satellite experiments [23]. It is observed that about 98 $\%$ of primary CRs in this region are hadrons and remaining 2 $\%$ are electrons and photons. In the hadronic component about 87 $\%$ consists of protons, 12 $\%$ helium nuclei, and the rest are ionized nuclei of heavier elements including iron. Beyond 10^{14} eV information on the CR mass composition can be known only through indirect methods. Our current knowledge is still not adequate to predict exact CR mass composition in the energy range from 10^{14} eV to just below 10^{17} eV. Above 10^{17} eV i.e. at the highest energies our knowledge about the CR mass composition is very limited.

Conclusions drawn on primary CR mass composition particularly in the PeV region from the analysis of variety of results obtained by various experiments indicate a trend in favour of a transition towards heavier elements beyond the *knee* energy [24]. But above 10^{17} eV, a change from a heavier to a lighter mass domination in CR composition is also reported.

1.2 Extensive air shower

Energies above 10^{14} eV, CRs interact with the atmospheric nuclei, and subsequently produce a cascade of secondary particles as shown in Fig. 1.2. This unique and perplexing event is known as EAS. Since its discovery by P. Auger [25], this remains the subject of utmost importance to CR physics, particle physics, and other interrelated fields. The detection of an EAS is not only useful for obtaining information on primary CRs but also play a pivotal role to the search of new particles as well as the phenomenology of ultra-high-energy interactions.

Secondary particles in an EAS are classified into three components; hadronic, muonic and electromagnetic. Electrons, positrons and photons are included in the electromagnetic component while charged muons constitute the muonic component. High energy hadronic interactions in the cascade produce short-lived mesons (mainly pions and kaons) of which many decay into muons, electrons and photons. In addition, there are fluorescence and Cherenkov photons, and very weakly interacting neutrinos and very fast muons. There is also radio emission from the propagation of lighter charged particles in an EAS. The Earth's atmosphere itself serves as large calorimeter for indirect search of high energy CRs.

1.2.1 Hadronic component

Although the majority of EASs are hadron initiated but hadronic component in an EAS is less than 1 %. But, this minority hadronic component largely affect the shower development because they feed the other shower components.

After entering into the Earth's atmosphere, a hadron strongly interact with air nuclei and produce first generation secondary particles. These first generation secondaries during their interaction with air nuclei or decays may produce next

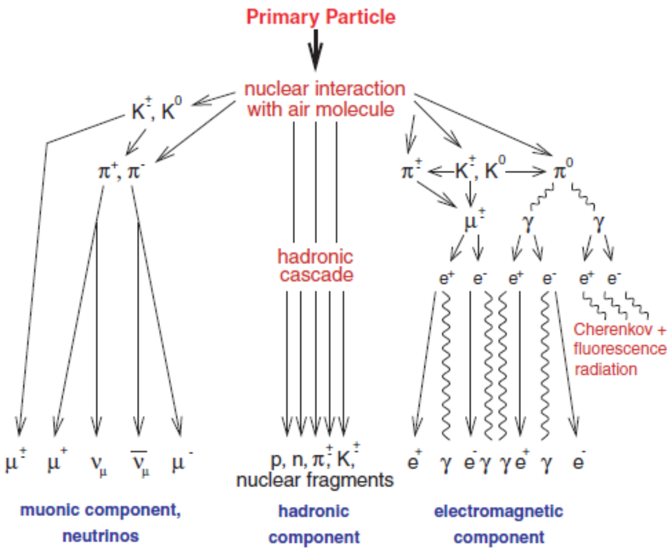

FIGURE 1.2: The schematic diagram of an EAS progeny (figure is taken from [26]).

generation of secondary particles. All these processes constitute a hadronic cascade with increasing number of hadrons as the atmospheric depth increases. During the cascade development each generation carries less energy compared to its previous generation. Due to this energy decrement, a secondary particle becomes more probable to decay, than to interact with air nuclei. From the depth of shower maximum in a cascade the number of hadrons decreases exponentially.

1.2.2 Muonic component

Besides electromagnetic component, muons contribute significantly to the total charged particle number in an EAS at the ground level. This is about 10 $\%$ of the total charged particle flux detected in an EAS experiment. The muons are mainly the decay products of charged pions and kaons.

$$\pi^{\pm} \longrightarrow \mu^{\pm} + \nu_{\mu}(\overline{\nu_{\mu}}) \tag{1.1}$$

$$\kappa^{\pm} \longrightarrow \mu^{\pm} + \nu_{\mu}(\overline{\nu_{\mu}}) \tag{1.2}$$

$$\kappa^{\pm} \longrightarrow \pi^{0} + \mu^{\pm} + \nu_{\mu}(\overline{\nu_{\mu}}) \tag{1.3}$$

Although mesons are main contributors of muons but a percentage of the muons is also contributed by charmed particles, such as $D^{\pm}$, D^{0}, J/ψ and others. Muons are generally co-produced with neutrinos (or anti-neutrinos) and the amount of neutrinos is building up as the EAS advances to the ground. Muon production rate is generally higher at the upper level of the atmosphere. Low air density in the upper level of the atmosphere favours mesons/kaons to decay before interacting.

The passage of muons through the atmosphere is mainly affected by ionization and is rarely affected by *bremsstrahlung*. At the later stage of an EAS most of the low energy muons can decay into electrons and neutrinos. For inclined showers ($> 50^o$), influence of the Earth's magnetic field on muons introduces an asymmetry in their lateral distribution around the shower axis.

1.2.3 Electromagnetic component

The electromagnetic component (positrons and negatrons / electrons) is the most abundant charged leptons (about 90 $\%$ of all the charged particles) in an EAS on the ground. They are created mainly from the decay of π^0 meson into two photons. The growth of an electromagnetic cascade in the later stage is governed by means of *pair creation* from photons and *bremsstrahlung* by electrons and positrons. In pair production, a photon generates an electron pair during its interaction with Coulomb field of nucleus.

$$\gamma + nucleus \longrightarrow nucleus + e^+ + e^- \tag{1.4}$$

The *bremsstrahlung* process caused by electrons and positrons during their interaction with the same Coulomb field of nucleus generate photons.

$$e^\pm + nucleus \longrightarrow nucleus + e^\pm + \gamma \tag{1.5}$$

After the shower maximum low energy photons are more abundant which then generate low energy electrons by Compton scattering and photoelectric effect in the cascade.

Suitable lateral density functions (LDFs) are used to describe the lateral density distributions of the electromagnetic and muonic components of an EAS initiated by protons and other nuclei. The LDFs for hadron induced showers were basically constructed empirically (by applying some modifications either to Moliére radius or slope/age parameter in the LDF found in the electromagnetic cascade theory) or seeded directly from the electromagnetic cascade theory. Here, we have used the well known Nishimura-Kamata-Greisen (NKG) structure function for hadron induced showers, that was basically derived approximately in the electromagnetic cascade theory for treating the electromagnetic showers. For describing the muonic component we have used both the types i.e. the NKG and the Greisen structure functions. A more detailed description of these different structure functions used in the present thesis will be discussed in subsequent chapters.

1.3 Air shower simulations

It is known that an EAS is the result of many complex processes in the field of high-energy nuclear and particle physics. Air shower simulation is the only key to unfold all these complex processes with the help of theoretical modelling of the cascade. An air shower simulation involves a detailed Monte Carlo (MC) calculations containing necessary physics of high/low energy hadronic and electromagnetic interactions. All these are taken care in a number of computer programs in such a way, so that the over all simulation program contains processes like propagation, interaction or decay and all other relevant processes in space-time and finally the information of all the significant observables.

1.3.1 The air shower simulation program *CORSIKA*

CORSIKA (**CO**smic **R**ay **SI**mulation for **KA**scade) is the basic program behind all the simulated results that would be presented in coming chapters. It is a most used simulation program comes from the standard and latest set of programs to describe almost all the aspects which appear in the development of a shower initiated by a CR particle.

The CORSIKA MC code [27] can simulate EASs with laboratory energies exceeding 10^{20} eV and all the intermediate interactions and decay of nuclei, hadrons, muons etc. are incorporated within. It gives us the information like location, energy, type, arrival times and direction of all the secondary particles created at any intermediate stage in an air shower.

The CORSIKA code has basically four parts in it. The first part is dedicated to handle the in and output, tracking of the particles, performing decay of unstable particles and taking into account the losses due to ionization, deflection due to Earth's magnetic field and multiple coulomb scattering. The high energy hadronic interactions of nuclei form the second part of the code. The third part of the code deals with the low energy hadronic interactions. The interactions and the transport of the electromagnetic components including photons are included in the fourth part of the code.

Different hadronic interaction codes are coupled with the CORSIKA MC code. These are Dual Parton Model DPMJET [28], HDPM [29], QGSJet [30, 31], SIBYLL [32, 33] or VENUS [34] or EPOS [35]. EPOS LHC (v3400) [36] is the latest model where results from LHC have been implemented. The low energy hadronic interactions are simulated by FLUKA [37], GHEISHA [38] or UrQMD [39] codes. Electrons and photons interactions are treated either with EGS4 [40] code or using analytic NKG function [41].

The main source of uncertainties in numerical simulations of EASs beyond LHC range are induced by the models which describe the hadronic interactions. Theoretical modelling of hadronic interactions is needed using extrapolation procedure to describe interactions beyond energies that exceed those attainable with man-made accelerators.

1.4 Objective of the thesis

The current trend of the CR research with EAS technique is to exploit as many of the EAS observables as possible from the analyses of EAS data. Such a strategy ensures the reliability of our findings and the validity of applied detection techniques, and hadronic interaction models.

The main objective of the proposed research work is to search relatively new CR mass sensitive air shower observables by exploiting different characteristics of EASs initiated by primary particles around the *knee* region from a detailed MC simulation. For implementing such a strategy, a number of new EAS analyses sensible to the CR mass composition are proposed. Moreover, the practical realization of these proposed techniques on real experiments are also under consideration in the work. In some cases, our results obtained on mass composition from these new analyses are compared with observed results available publicly from the NBU and KASCADE experiments.

1.5 Organization of the thesis

This thesis is based on my completed research works which were proposed initially. The whole content of the thesis is organized as follows:

• In **Chapter 1** a brief overview on the discovery of CRs is described. Basic elements of CR physics particularly in the PeV region of their energies are introduced. Various features present in the energy spectrum of CRs are described. Importance of the CR mas composition around the *knee* is discussed. Basic features of EAS and its detection are also described. A brief description on the air shower simulation is also presented.

• In **Chapter 2** results of the investigation by different experiments in the concerned energy region are reviewed. Different detection techniques for an EAS and the corresponding measurement, and analysis of the EAS parameters for estimating the mass composition of CRs are discussed. Important conclusions that are drawn by different experimental groups on the mass composition of CRs is finally summarized.

In the following *five* chapters author's original research on CR mass composition is discussed.

• In **Chapter 3** we have studied the lateral distribution of electrons in EAS by analyzing CORSIKA generated shower events in the *knee* region. The study takes into account the issue of the lateral shower age parameter associated with the lateral distribution of electrons as an indicator of the stage of development of EASs in the atmosphere. A multi-parameter study of EAS is exploited to correlate the lateral shower age parameter with other EAS observables to identify the nature of the shower initiating primaries. Using KASCADE data we have found a transition from light to heavy mass composition around the *knee*.

• In **Chapter 4** we address some aspects of the local age and segmented slope parameters (LAP and SSP) of the lateral density distribution of EAS electrons and muons, from a detailed simulation study. We check the validity of one-parameter scaling representation of lateral density distribution of muons through the local age or the segmented slope. This study also correlates these parameters with other EAS observables for examining the possibility of utilizing observed shape parameters obtained from available published KASCADE radial density data for electrons and muons, in order to deduce CR mass composition.

• In **Chapter 5** we have quantitatively described the asymmetry in the lateral density distribution of electrons due to atmospheric attenuation in case of non-vertical showers. This asymmetry is quantified in terms of new EAS observable, called the gap length parameter. The dependence of the parameter on different known air shower observables is also included. We have constructed an elliptic lateral density function by modifying the NKG function to get more precise estimation of EAS parameters. The radial dependence of local age parameter as well as its mass sensitivity is also studied with this modified elliptic lateral density function.

• In **Chapter 6** an estimation of the mass composition and more importantly the energy of CRs above 100 TeV based on the lateral distribution of EASs is made. We have shown that the determination of primary energy of a CR particle might deliver a better accuracy compared to standalone analysis.

• In **Chapter 7** we have made a detailed analysis over the asymmetry in the abundance of positive and negative muons in an EAS with high zenith angle as a consequence of the influence of the Earth's geomagnetic field. The asymmetry has been quantified by a parameter called the transverse muon barycentre separation. The polar variation of this parameter and its maximum value exhibits sensitivity to CR mass composition. Possibility of practical realization of the proposed method in a real experiment is also discussed.
In this chapter we have attempted to make a link between variations in Earth's geomagnetic activity and EAS muons. It is expected that the idea will also be useful for making a geomagnetic calculator based on the behavior of muons in EAS under the influence of the Earth's magnetic field.

• In **Chapter 8** the thesis on CR mass composition is discussed.

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