Chapter 1

Cosmic Rays and Extensive Air Showers

1.1 Introduction

Highly energetic charged (nuclei, electrons, positrons) and neutral (neutrinos, photons) particles coming from outer space and hitting earth's atmosphere are generally referred as cosmic rays. These were first discovered by Hess in 1912 [1] during several balloon flight experiments. The energy spectrum of these particles spreads over a wide range of energies, from a few hundred MeV to more than 10^{20} eV, the flux of which can be described well by a power law

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

whose main feature is the so called knee, a change in the spectral index , γ from 2.7 to 3.1, at about 3×10^{15} eV as shown in Fig. 1.1. The measurement techniques are different depending on the involved flux. In fact, over the entire energy range, the integral flux drops from 1 particle m^{-2} s^{-1} at 10^{11} eV, to 1 particle m^{-2} $year^{-1}$ at 10^{15} eV, down to 1 particle km^{-2} $century^{-1}$ at 10^{19} eV. A further steepening of the spectrum (the second knee) has been claimed recently around 4×10^{17} eV, which is called as the *iron knee*. The spectrum gets flattened at about 4×10^{18} eV, giving rise to another interesting feature, the *ankle*.

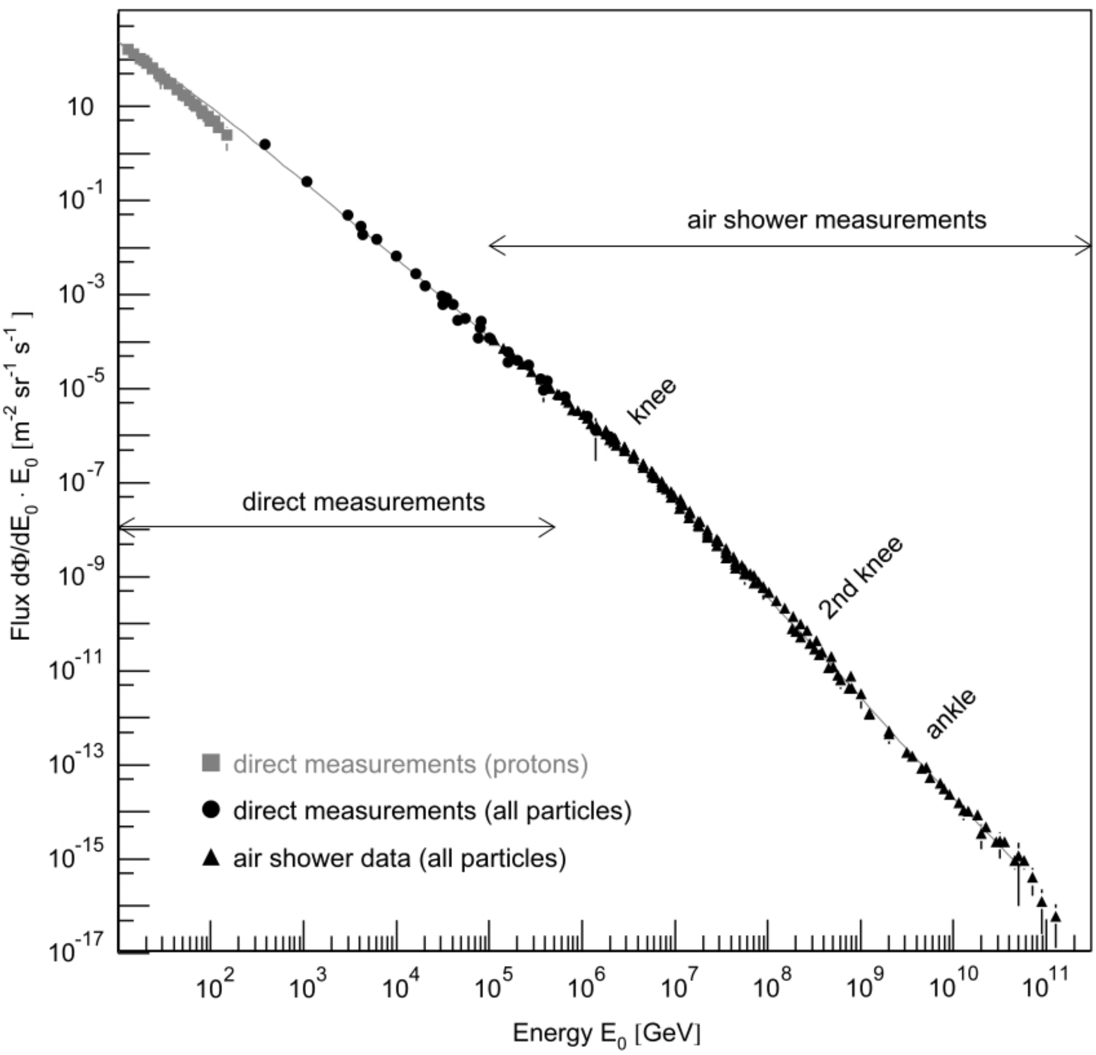

FIGURE 1.1: The differential energy spectrum of PCR and its various important features like the *1_{st} knee*, the *2_{nd} knee* and the *ankle* (figure taken from [2]).

The *knee*, a sharp turn in the energy spectrum of cosmic rays around 3 PeV , is an important characteristic feature of the spectrum which demonstrates a sudden decrease in spectral slope. The study of the knee has been an important topic of research both in experimental and theoretical astroparticle physics world wide since it was first detected in the studies of Moscow State University group in 1958 [3, 4]. For the following (fifty seven) years, quite a few experiments have been confirming the existence of this knee, displayed by various observable, mapping the primary CR spectrum. The existence of knee in the energy spectrum of the primary CR is an important imprint of the true model for origin of cosmic rays and hence proper understanding of this spectral feature is vital in connection with the problem for origin of cosmic rays.

Several mechanisms have been proposed to explain the knee which is discussed in detail in Chapter 2. In their first conclusion the discoverers argued that the knee in the spectrum is a consequence of the superposition of cosmic rays of galactic and extragalactic origin [5]. In subsequent years many new ideas have been proposed which vary from astrophysical reasons such as leakage from the galaxy due to reduced efficiency of galactic magnetic field to confine the cosmic ray particles within galaxy [6–14], rigidity cut-off at the acceleration [15], nuclear photo-disintegration at the sources [16, 17], or the single-source model in which dominance of the flux at the knee is coming from a nearby supernova [18–20] to a scenario adopting a new channel of the primaries interaction producing new unobserved particles carrying away some energy [21, 22]. Sveshnikova has ascribed the knee as the result of cosmic ray acceleration by a variety of supernovae [23–25]. On the other hand employing improved analysis techniques spectra for individual elements or mass group around the knee of the spectrum have been obtained from modern experiments through simultaneous measurements of many observables [85]. These results indicate rigidity dependent breaks; the knee is due to the steepening of proton/light elements spectra. But none of the existing models of the knee are free from problems. For instance, if the knee corresponds to break in proton spectrum then maximum energy of iron flux from the same sources should be around 10^{17} eV. Hence a special variety of supernovae or some other type of galactic source has to be invoked as generator of cosmic rays between 10^{17} eV and the ankle. The problem with such a fine-tuning is to match both the flux and the energy at the point of taking over. Moreover, it is already been noticed that rigidity dependent break scenario of composition does not consistently described the whole data set of the measurements over the whole energy region. Though single source model can avoid such criticisms but a problem with the proposal is that in normal circumstances the source should be observed in high energy gamma rays but no strong evidence for gamma ray emission from any nearby SNR exists. The change in interaction scenario at the knee energy has not received any support from the accelerator experiments against the expectations. In Chapter 6, we shall propose a new theoretical model for the knee.

The tail of the CR spectrum, above 10^{20} eV, is scarcely populated. A cut-off is predicted by Greisen, Zatsepin and Kuzmin (GZK cut-off) [26–28] at 5×10^{19} eV , due to the interaction of the primary particles with the photons of the cosmic microwave background (CMB) radiation. The highest energies of the cosmic ray spectrum are studied by the Pierre Auger Observatory [29, 30] with good statistics which has observed a sharp decrease of flux around 5×10^{19} eV which could be the GZK cut-off.

1.2 Composition of cosmic rays

The chemical composition of cosmic rays is estimated from direct measurements up to energies below 10^{14} eV. The estimation of elemental distributions have been studied by satellite [34–48] and baloon flight experiments [49–65] up to energies of 1-2 TeV/nucleon. It is found about 98% of cosmic radiation are hadrons out of which 87% are protons,12% is Helium and 1% corresponds to charged nuclei of heavier element like Fe, C, N, O, B etc.

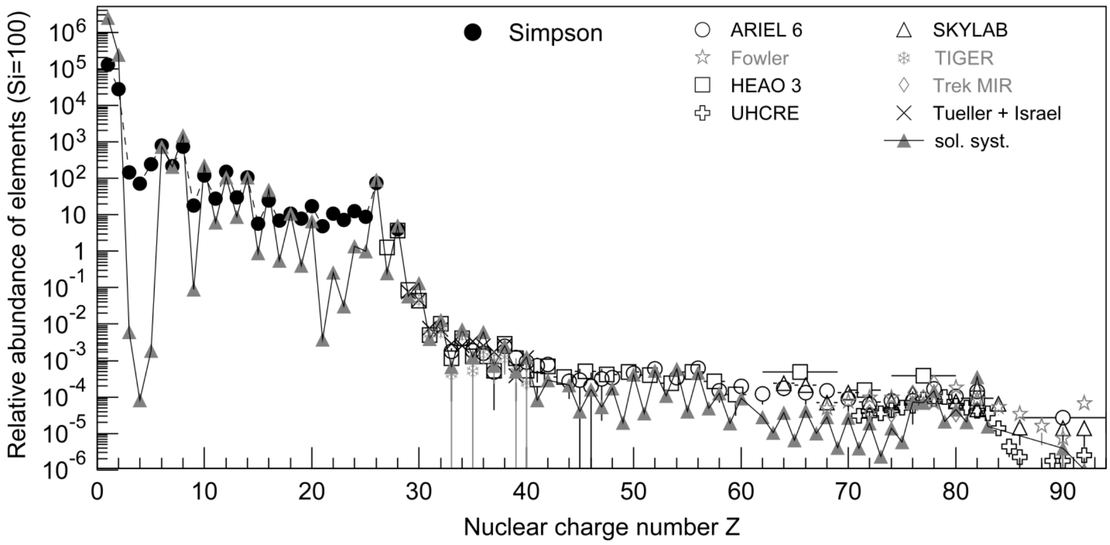

Figure 1.2: Comparison of the relative abundance of elements as a function of Z in the solar system and the primary cosmic radiation at source around 1 GeV/n, normalized to Si = 100 [31]. Data for $Z \leq 28$ is from [32] where as data for heavy nuclei are taken from ARIEL 6 [37, 38], HEAO 3 [39], SKYLAB [40], TIGER [41], TREK/MIR [42, 43] and UHCRE [44]. Data showing the abundance of elements in the solar system is taken from [33]. This figure is taken from [2].

As shown in Fig 1.2, the comparison of relative elemental abundances in the solar system with the derived abundance at the sources has similarities, suggesting that cosmic rays are accelerated out from a sample of well mixed interstellar matter. In cosmic rays, elements like Li, Be, and B are overabundant, as well as all the groups with atomic mass lower than Fe. No significant difference is found, instead, in the abundances of heavier elements. But in cosmic rays lighter elements like Li, Be and B are abundant. So it is believed that while propagating through galaxy, lighter elements are generated by the process of spallation when heavier nuclei interact with interstellar medium. After that they got trapped into the galactic magnetic field with trapping time period about 10^7 years. As most of the primary particles are charged hadrons, their path is affected by the galactic magnetic field because of which it is impossible to locate the original source.

The composition scenario evolve from indirect observations involving air shower studies is not unequivocal. Recent results favour that the composition shifted towards heavier elements beyond the knee. At higher energies, an evolution from iron dominated composition at 10^{17} eV to a proton dominated composition above 10^{18} eV is reported by some experiments .

1.3 Extensive air showers(EAS)

The highest energies reached by cosmic rays are much larger than the ones produced in any of the present and forthcoming colliders (i.e. TeVatron and LHC). From Fig. 1.3 in which the cosmic ray energy spectrum is compared with the laboratory energies of the colliders, it can be understood how air shower phenomena can work as a great natural laboratory giving the opportunity to compare and considerably enlarge the field of view on particle physics.

Extensive air showers were first studied in 1938 by P. Auger et al. [66] and independently by W. Kohlhorster et al. [67], which is nothing but a stream of secondary particles generated in the Earth's atmosphere when highly energetic cosmic ray particles interact with air molecules multiple times (Fig. 1.3). The resulting secondaries while propagating in downward direction suffer repeated collisions with air molecules generating billions of particles (depending on the primary energy) that gain transverse momenta because of the repeated collisions. At the end, mostly electrons, muons and gammas are observed. Due to this fact, the EAS is usually spread over a large area with a thickness increasing with the distance from shower axis which is represented by the incident direction of the primary. Spread of an EAS depends on energy of the primary particles. Distribution of the arrival times of these particles also gives us some idea about the direction of primaries.

After the first interaction of a primary cosmic ray particle with Earth's atmosphere, its energy is dissipated by secondary interactions, resulting secondaries

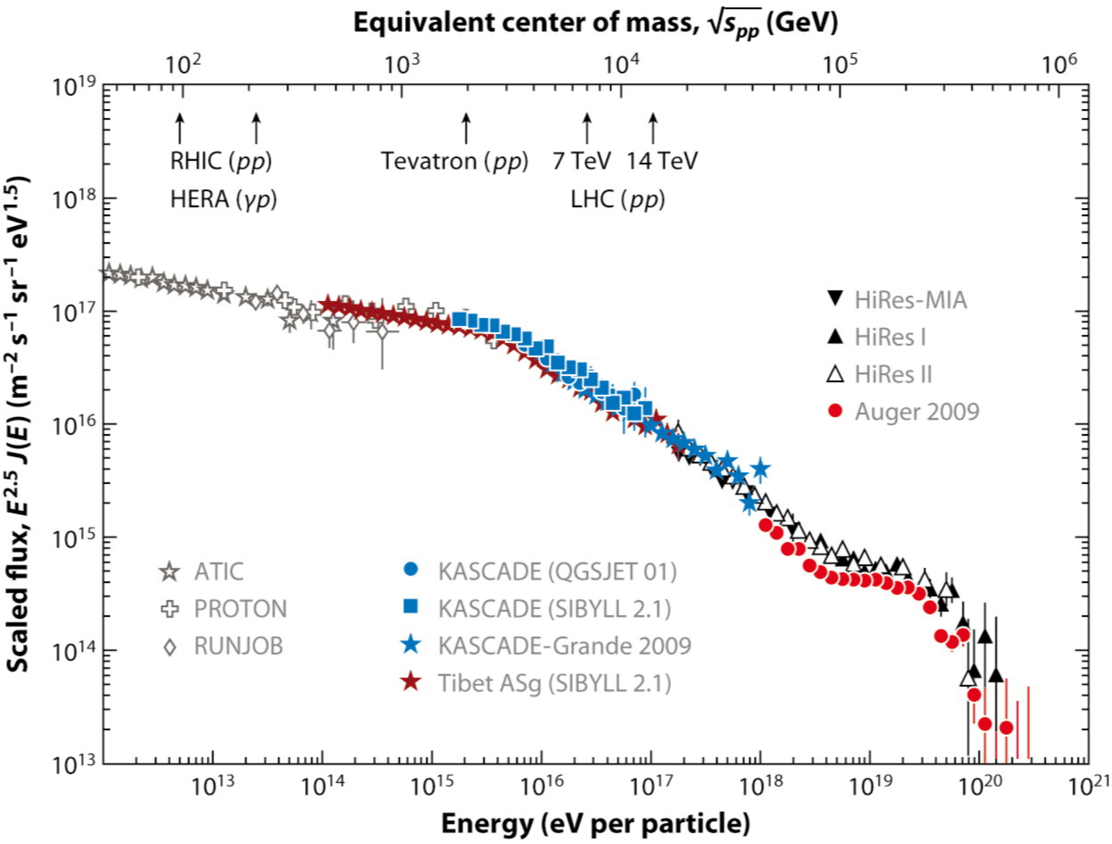

FIGURE 1.3: Primary cosmic ray energy spectrum and the equivalent beam energies of the RHIC, Tevatron and Large Hadron Collider (figure taken from [68]).

which again interacts with air while propagating in downward directions. So the number of secondaries increases as a shower propagates. Also the EAS particles suffer decay and absorption during its propagation. The dominating electromagnetic component (photons and electrons) is usually the one absorbed faster in both time and with distance to the point of first interaction and shower core. Other components are more penetrating like the muon component. At the earlier stages of a shower, the production process of secondaries dominates over the absorption and decay because of the energetic secondaries, resulting an important feature X_{max}, the altitude at which the number of secondaries are maximum. This plays an important role in the estimation of cross section of primary particles with air nuclei.

There are thee main components of EAS at the sea level, electromagnetic, muonic and hadronic.

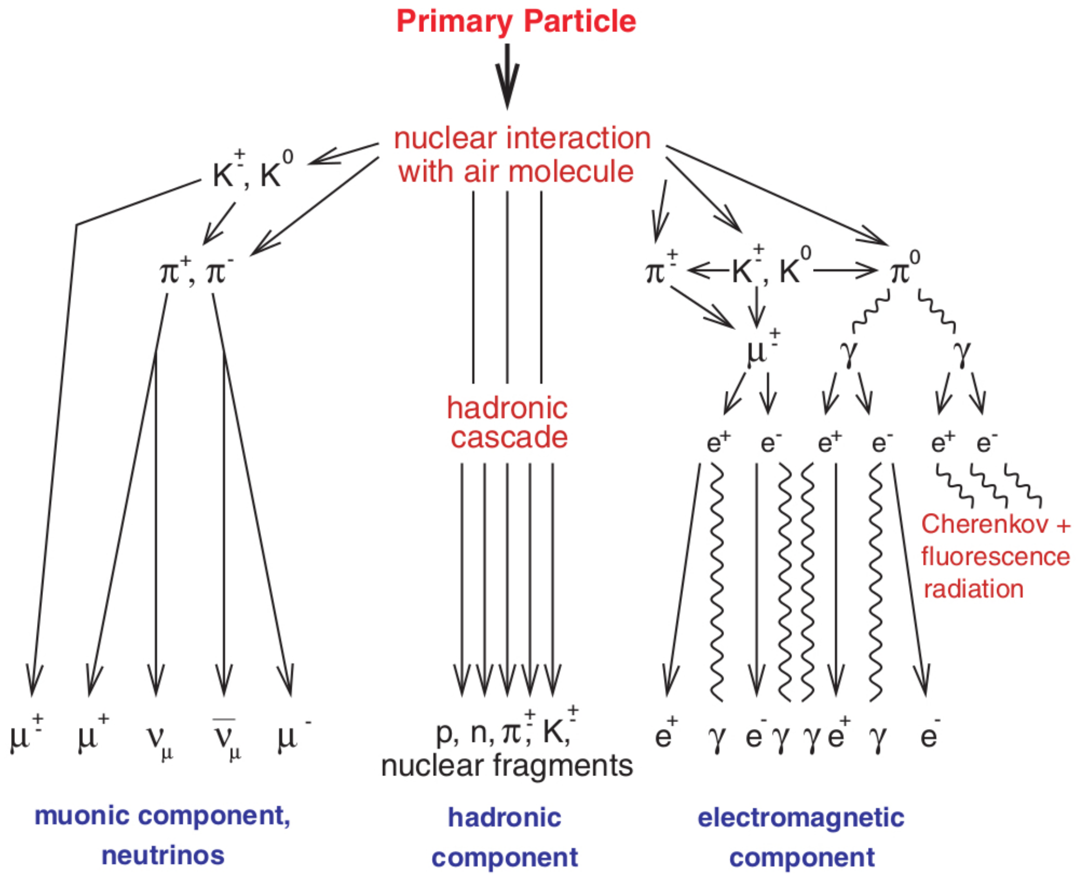

FIGURE 1.4: Schematic diagram of an EAS initiated by the interaction of a PCR particle with the Earth's atmosphere (figure taken from [69]).

The electro magnetic components constitute mainly electrons and photons. At sea level, 95% of particles are electromagnetic out of which about 85% of particles are γ rays and rest are electrons and positrons. When primary cosmic ray particles interact strongly with an air molecule of Earth's atmosphere, mostly mesons are produced which gives us an idea about multiplicity. Among these many produced particles, one particle carries great fraction of the incident primary energy, the fraction being called elasticity. The fraction of energy that is not given to that particle is called inelasticity. The inelastic part of energy is distributed among rest of the secondary particles.

Most of these produced mesons are pions and kaons. The neutral pions decays instantly into γ rays after its production.

$$\pi^0 \longrightarrow \gamma + \gamma$$

These γ rays start electromagnetic avalanches by pair production $(e^- + e^+)$ and by bremsstrahlung processes. When electrons and positrons reach an energy level of about 100 MeV, energy loss by ionization starts to become important and the particles are stopped quickly. After reaching its maximum size, the particle number in the EAS decreases approximately in an exponential way. The charged mesons either interact with atoms of the atmosphere or decay into muons and neutrinos(anti-neutrinos).

$$\pi^{\pm} \longrightarrow \mu^{\pm} + \nu(\bar{\nu})$$
$$K^{\pm} \longrightarrow \mu^{\pm} + \bar{\nu}(\nu)$$

Muons form the penetrating EAS component since they get less absorbed and reach the ground with high probability (the higher energy muons can penetrate in the deep underground). This is also due to their comparatively long lifetime, which is enlarged by relativistic time dilatation. The decay of charged muons lead to the generation of decay electrons that add to the electromagnetic component. Together with electron, muon forms the charged particle component with the integrated intensity (shower size) N_{ch}. For not too inclined EAS, the shower size is sometimes considered more or less equivalent to the electron size.

$$N_e \approx N_{ch.} \tag{1.2}$$

Finally, the core of an air shower is situated around the shower axis and consists of the hadronic component containing mostly pions but also nucleons, antinucleons, K-mesons and more exotic particles.

In order to measure the sizes of the different components, a typical EAS experiment uses an array of detector stations covering a large area in the 10^3 m^2 range and records the lateral particle densities distributions by sampling the area of various kinds of detectors. Then, using an a-priori assumed form for the lateral distribution (lateral distribution function) of the particles, size is determined.

The three main EAS components, whose developments usually studied, are accompanied by Cerenkov, nitrogen fluorescence and radio emission in the atmosphere. Each component provides specific observables that carry information about the primary particles. Depending on the kind of observable one wants to record, different types of detector systems are used leading in many cases to the installation of complex detector systems capable of detecting different components of the same EAS simultaneously. By such a detection system, correlated studies among different observables become possible.

EAS measurements are difficult because the primary energy and composition are unknown and have to be indirectly inferred from a precise determination of the EAS observables and deep theoretical assumptions on the shower interactions. Investigation of EAS which has been in former times directed to explore the inherent features, the development and structure of the phenomenon, is nowadays mainly focused to the understanding, in which way some features can be related to the energy and mass of the primary and can be used as signatures for these primary properties. Simulation studies have demonstrated that, on the average, heavy ion induced air showers develop differently from proton induced showers due to a smaller interaction length and due to a larger number of nucleons in the projectile. This is corroborated by the effect that the multiplicity of secondary particle production per nucleon varies only slowly with the energy. Thus the muon content of an iron induced EAS appears to be larger than for the proton induced one. Simultaneously the number of electromagnetic particles (e/γ) gets larger in the proton EAS because their energies reflect the energy of neutral pions they originate from. As electrons and positrons are rapidly absorbed when their energies drop below 100 MeV, an A-nucleon shower, with each nucleon carrying the energy E/A, reaches earlier the maximum of its longitudinal development, i.e. higher in atmospheric altitude. That means for the same primary energy E, the shower size (N_e) is different for different kind of primaries observed at the observation level. Since we neither know a-priori the energy nor mass of the primary, energy determination and mass discrimination is an entangled problem. Therefore many attempts are focused to minimize the influence of mass on the observable which serves as the energy estimator.