Chapter 1

Introduction

Cosmic rays are highly energetic particles originating in outer astrophysical sources, that travel at nearly the speed of light and are impinging on the Earth from all directions. Cosmic rays consist of hadrons, heavy-nuclei, photons, neutrino and very small amount of stable anti-particles. About 90% of the cosmic rays are proton, about 9% are alpha particles and about 1% are heavier particles [1]. Rarer nuclei were identified using nuclear emulsion plates exposed to primary cosmic rays, and now many nuclei, up to uranium, have been found [2].

1.1 Discovery

Pioneer cosmic ray experiment was carried out in 1909 by Father Theodor Wulf, a Jesuit priest [3] who went up the Eiffel Tower and performed a series of measurements for four days to measure the ionisation of the air. He measured more radiation with his electrometer than he expected. Wulf guessed that the radiation might have extraterrestrial origin and he proposed going up in balloons to greater heights to verify the idea. But he could not make the adventure due to lack of funds. This risky endeavor was undertaken by the Austrian physicist, Victor Franz Hess During 1911-12 he made ten ascents in balloons reaching heights of over 5000m. These series of experiments showed that the intensity of the radiation increases rapidly above 1000m. The intensity was found to be three to five times greater at 5000m altitude than that at sea level. He used sealed, pressure tight electrometers, to keep the particle number density inside the apparatus constant during these balloon ascents. Three independent electrometers were used for ionisation measurements during the flight. Hess concluded that there must be a powerful radiation originating in outer space. While entering the Earth’s atmosphere, intensity of radiation
diminishes as it passes through the air towards the ground.

During 1907 to 1910, Domenico Pacini an Italian, who was an assistant meteorologist in Rome, performed a series of systematic investigations of ionization on mountains, on the shore-line, over a lake, and over the sea (Livorno and Genova gulf few miles from the coast) in 1907 and also 3m under the sea water in front of the Naval Academy of Livorno in 1911 (and later in the Lake of Bracciano). The instruments Pacini used had a sensitivity of one third of a volt. He found the ionization in underwater to be 20% lower than that at the surface. Thus Pacini concluded that a certain part of the ionization must be due to sources other than the radioactivity of the Earth crust [4].

During the mid-1920s Robert Millikan’s group at the California Institute of Technology developed an electrometer whose readings could be recorded on a moving film automatically. With this electrometer, unmanned balloons could take the records of ionisation at very high altitudes. Millikan initially had not believed Hess’s claims. He made extensive investigations of his own, and in 1926 he finally accepted that the radiation came from outer space. Due to the high penetrating nature, Millikan and many others believed that the cosmic rays are ultra-high-energy gamma radiation. Nobel Prize in 1936 was awarded to Hess for discovering the cosmic radiation. Millikan is honoured through commonly used name ‘cosmic rays’, which he coined.

The intensity of the cosmic radiation is very low, even at high altitudes. Again, the cosmic rays are more energetic and less ionizing than the lower-energy rays from radioactive sources. A radioactive source can be set to provide a narrow, well-defined beam of radiation; whereas, cosmic rays strike the Earth from all directions. This feature posses additional complexity. Bruno Rossi at the University of Florence found a way of using electronic valves to register coincident pulses from the Geiger counters. Rossi used three counters arranged in a triangle so that a single particle could not traverse all three counters. Rossi detected many coincident signals from all the counters. This showed for the first time the production of showers of secondary particles. Results from ‘coincidence experiments’ with Geiger counters, particularly those by Rossi, showed just how penetrating the cosmic rays are. They can pass through metre-thick lead plates and have even been detected deep underground, thousands of metres below the surface of the Earth. But because of their high energies and consequent low ionizations, identifying the exact nature of the particles present in the rays was nearly impossible at that time.
1.1.1 Origin

It is about one hundred year long question — "What are the origin of such energetic rays?". Origin of cosmic rays is associated with the dynamics and processes related with the star formation, stellar evolution and supernova explosion etc. and various acceleration mechanisms in the Galaxy. One possible source is supposed to be the violent outburst of a supernova. The material blown out in this process burst so quickly that it creates shock waves. The acceleration mechanism is known as Fermi acceleration in shock-borne magnetic fields. Whenever a proton crosses the shock wave boundary, it encounters a giant kick and gains an increase in speed of about 1%. As protons have charge, they get trapped into the intergalactic magnetic field. Thus protons repeatedly have to cross the shock boundaries and gain energy cumulatively large enough to escape from the shock region. Origin of ultra high energy cosmic rays is extragalactic. Possible sources include Active Galactic Nuclei (AGN), pulsar, quasar, neutron star and gamma ray burst.

1.1.2 Energy Spectrum

The energy spectrum follows a broken power law $dN/dE = E^{-\alpha}$. At about $3 \times 10^{15} \text{eV}$ — the ‘knee’ of cosmic ray spectrum, power index steepens from $\alpha=2.7$ to $\alpha=3.0$. Again at about $2 \times 10^{17} \text{eV}$ — the ‘second knee’ of cosmic ray spectrum, power index steepens from $\alpha=3.0$ to $\alpha=3.1$. Again another change of power index from 3.1 to 2.6 at about $3 \times 10^{18} \text{eV}$ is called the ‘ankle’ [5]. It is assumed that cosmic rays up to and even beyond the knee are of Galactic origin. The main accelerator candidates are supposed to be the supernovae remnants (SNR). The shock fronts from supernova explosions propagate into the interstellar medium. Particles gain energy in the scattering processes across the shock front repeatedly.

The spectrum resulting from first-order Fermi acceleration can be shown to follow roughly an $E^2$ spectrum, with a maximum energy

$$E_{\text{max}} \propto Z.v.B.L \quad (1.1)$$

where $Z$ is the charge of the particle, $v$ the velocity of the shock wave, $B$ the magnetic field strength in the acceleration region and $L$ the size of this region. With Eq. 1.1, a SNR can boost particles up-to energies about $10^{14} \text{eV}$. However, additional interactions of cosmic rays with the magnetic fields can boost energies up to $10^{16} \text{eV}$ [6]. The mechanism of converting kinetic energy of the SNR into energy of accelerated particles is effective over
the first $10^3-10^4$ years of the SNR. Galactic energy budget also provides the circumstantial evidence that SNRs may be the main sources of cosmic rays. The energy density of Galactic cosmic rays is $\approx 1\text{eV/cm}^3$ [1], corresponding to cosmic ray energy density $\rho_{CR} = 10^{-12}\text{erg/cm}^3$. The power required to sustain this density is $P = \rho_{CR} \cdot V / t_{cont}$, with $t_{cont} \approx 10^7$ years [7] is the average containment time of cosmic rays in the Galaxy and $V \approx 10^{67}\text{cm}^3$, the volume of the visible part of the Galaxy. Supernovae release on average $10^{51}\text{erg}$ every 20-50 years [$\approx 10^{42}\text{erg/s}$], as estimated by Baade and Zwicky [8]. Thus $P \approx 10^{41}\text{erg/s}$, the power to maintain the cosmic ray density is about 10% of the power generated by supernovae. There are more probable candidates for cosmic ray acceleration. These are pulsars with their extremely high magnetic fields at the poles, and binary
systems with a neutron star or a black hole as one of the partners, and, relativistic radio jets etc. [10, 11]. Somewhere between $10^{17}$ and $10^{18.5}$eV, cosmic ray spectrum is dominated by extragalactic sources. At about $10^{18.5}$eV, the ‘ankle’, the spectrum flattens again to have $\alpha = E^{2.7}$ and CR above the ankle are assumed to be of extragalactic origin. Cosmic rays with this much of energy have their gyro-radius beyond the size of the Galaxy. The cosmic microwave background was first observed by Penzias and Wilson [12] in 1965. The cut-off of the cosmic ray spectrum, the ‘GZK cut-off’ at highest energies is due to interactions of cosmic rays with the cosmic microwave background and was first predicted by Greisen [13], Zatsepin and Kuzmin [14]. The Cosmic Microwave Background Radiation (CMBR) has an average temperature of 2.7K. In the rest frame of the proton, photons from CMBR have energies greater than the threshold for inelastic pion photo-production. The proton and photon excite a $\Delta^+$ resonance, which decays into a proton and $\pi^0$ or a neutron and $\pi^+$ as follows

$$
\begin{align*}
  p + \gamma_{\text{CMB}} &\rightarrow \Delta^+ \rightarrow p + \pi^0 \\
  p + \gamma_{\text{CMB}} &\rightarrow \Delta^+ \rightarrow n + \pi^+ .
\end{align*}
$$

These reactions given by the Eq. 1.2 become important at approximately $5 \times 10^{19}$eV. The interaction length is $\sim 6$Mpc, and the energy loss per interaction is about 20%. This energy loss will produce the break in the energy spectrum at these energies for sources more distant than $\sim 100$Mpc.

The ‘GZK cut-off’ is well confirmed by HiRes, Telescope Array (TA), AGASA and Yakutsk detectors, Auger detector [15, 16].

The main possible candidates for particle acceleration to energies beyond $10^{19}$eV are Active Galactic Nuclei (AGN), Gamma Ray Bursts (GRB) and star-burst galaxies which can accelerate protons up-to $10^{21}$eV. The power required to sustain an $E^{-2}$ flux up to GZK energies i.e. energy density of $\approx 10^{-7}$eV/cm$^3$, equivalent to $3 \times 10^{19}$erg/cm$^3$ [17]. Normalised to the cosmic abundance of AGN and GRB, this corresponds to a power of about $2 \times 10^{44}$erg/s (Active Galaxies) and $3 \times 10^{52}$erg/s (Gamma Ray Bursts) [17]. The electromagnetic energies released by these objects correspond to a similar order.

To study requirements of the possible candidate sources an upper limit to the maximum energy of acceleration was found from condition of equality of the Larmor radius and dimension of the accelerating site. The Larmor radius is given by,

$$
\tau_L = \frac{E}{ZeB} \sim 110 \text{kpc} \left( \frac{\mu G}{ZB} \right) \left( \frac{E}{100 \text{EeV}} \right)
$$

(1.3)
Figure 1.2: Updated Hillas (1984) diagram. Above the upper blue line for protons (lower red line for iron nuclei) cosmic rays can be confined to a maximum energy of $E_{\text{max}} = 10^{20}\text{eV}$. The most powerful candidate sources are shown with the uncertainties in their parameters [18].

The lifetime $\tau_L$ of UHECRs in Galactic magnetic fields is much larger than the thickness of the Galactic disk [18]. Thus, magnetic confinement in the Galaxy is not maintained at the highest energies. Search for extragalactic sources capable of confining particles up to $E_{\text{max}}$; necessary but not sufficient selection criterion for candidate sources is given by famous “Hillas plot”. The candidate sources are placed in a BR phase-space, taking into account the uncertainties. Most astrophysical objects do not even reach the iron confinement line up to $10^{20}\text{eV}$. For required UHECR acceleration the Hillas criterion is satisfied by neutron stars, AGNs, GRBs, and accretion shocks in the intergalactic medium [18].

1.1.3 Extensive Air Shower (EAS)

The phenomenon of Extensive Air Shower was discovered by Auger and his collaborators in 1938 [19]. High-energy cosmic rays enter into the Earth’s atmosphere and interact with air nuclei resulting cascades of secondary particles known as extensive air showers (EAS). Primary hadronic interactions of a proton or a nucleus with air results many hadrons...
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Initially, these secondary hadrons either decay or interact with air again to result further hadron production, and so on. This is known as hadronic cascade.

\[ \text{Primary Particle} \]

- \( K^+, K^0 \)
- \( \pi^+, \pi^- \)
- \( \mu^+, \mu^- \)
- \( \nu_\mu, \bar{\nu}_\mu \)
- nuclear interaction with air molecule
- hadronic cascade
- nuclear fragments
- electromagnetic component
- muonic component, neutrinos

In the upper atmosphere, due to smaller atmospheric density, hadrons may decay before they undergo subsequent interactions [20]. For example, the lifetime of a charged pion is \( \approx 10^{-8} \text{s} \), so, it will decay as follows:

\[ \pi^\pm \rightarrow \mu^\pm + \nu(\bar{\nu}) \text{ (100%)} \]

Further \( \pi^0 \) has a life of \( \approx 10^{-17} \text{s} \) and decays as

\[ \pi^0 \rightarrow 2\gamma \text{ (98.8%)} \]

whereas, \( K^\pm \) with average life time of \( \approx 10^{-8} \text{s} \) will decay as

\[ K^\pm \rightarrow \mu^\pm + \nu(\bar{\nu}) \text{ (63%)} \]  \( (1.4) \)

Muons have lifetime of \( \approx 10^{-6} \text{s} \). They do not undergo strong interactions with other particles. Thus muons have higher order of attenuation length as compared to neutrons.
and protons. Therefore muon flux decreases slowly with depth in comparison to other hadronic components [20]. Thus muon contribution to the multi-particle production becomes significant as the atmospheric depth increases. Some of energetic muons at ground level even reach deep underground.

1.1.4 Photon Electron Cascade

Each γ initiates an electromagnetic (EM) cascade consisting of photons and electrons. Photons and electrons undergo various interactions. i) Pair production – production of electron-positron pair when high energetic photon interacts with the Coulomb field of air nucleus – is the most relevant in the early stage of EM cascade development. ii) Compton scattering due to the interaction of low energetic photons with electrons is significant in the later stage or away from the shower axis. iii) Bremsstrahlung - the energetic electrons slowed down due to the interaction with the Coulomb field of air nucleus to radiate photon – is relevant in the early stage. iv) Ionisation loss by electrons at a later stage of the cascade.

1.1.5 Electromagnetic Component

Showers initiated by photons or electrons are known as electromagnetic showers. The particle production processes, bremsstrahlung of electrons and pair production of electrons by photons are dominant for em shower. Electrons are subjected to the radiative energy losses, and ionization energy losses. The total energy loss $dE/dX$ of electrons can be written as

$$\frac{dE}{dX} = -\alpha(E) - \frac{E}{X_R},$$

where $\alpha(E)$ is the ionization energy loss depending logarithmically on energy which is given by the Bethe-Bloch formula. $X_R$ is the radiation length and in air $X_R \approx 37 \text{ g/cm}^2$. In shower development process, the more the ionization energy loss, lesser is the particle production and vice-versa. At critical energy, ionization loss and energy loss due to particle production are the same. For electron the critical energy, $E_c \approx 86\text{MeV}$. Bhabha and Heitler first gave the theory of cosmic showers for electromagnetic cascade in the atmosphere in 1937 [21, 22]. This analytical model is very useful for basic understanding of the shower development process. In this model, it is assumed that the incoming particle with energy $E_0$, after travelling a depth known as interaction length $\lambda_{em}$, splits into two particles recursively. This process will continue until the energy of the particles become
smaller than the critical energy $E_c$. Energy of the new particles are half the energy of the initial particles. After $n$ successive interactions, the number of particles will be $2^n$. The number of particles as a function of depth $X$ is given by $N(X) = 2^{(X/\lambda_{em})}$. The maximum number of particles in the shower is given by $N_{max} = E_0/E_c$. The depth of shower maximum at which $N_{max}$ will occur is given by

$$X_{max} = \lambda_{em}\log_2(E_0/E_c).$$

From Eq. 1.6, it is seen that the number of particles at shower maximum is proportional to the primary energy and the depth of shower maximum is proportional to the log of primary energy.

At very high energy, Landau-Pomeranchuk-Migdal (LPM) effect, magnetic pair production and bremsstrahlung become significant for em shower. LPM effect is due to the quantum mechanical interference of amplitudes from different scattering centres. In the early 1950's, a group of Russian theorists, led by Landau, Pomeranchuk, Migdal and Feinberg, while studying bremsstrahlung they realised that bremsstrahlung is not instantaneous but occurs over a finite formation zone. That’s why the low longitudinal momentum transfer between the nucleus and the electron occurs in bremsstrahlung. During this time sufficient external influences can perturb the electron and suppress the photon emission. At low energy the amplitudes of subsequent interactions of photons or electrons are independent of the former interactions. But at very high energy, coherent interference of these amplitudes suppresses both the pair production and bremsstrahlung cross sections at very high energies. In air, the LPM effect becomes important at energies above $10^{18}$eV, which results stretching of the cascade at the initial phase due to slower rate of development. Thus it penetrates deeper into the medium resulting increase in $X_{max}$. Again Gamma-rays above energies $10^{19.5}$eV start interacting with the geomagnetic field of the Earth thousand kilo-meters above the atmosphere to produce positron electron pairs. The newly created electrons undergo magnetic bremsstrahlung to result a cascade of few hundred of secondary photons and a few electrons, which enter and interact in the atmosphere simultaneously. The primary energy is shared by many secondary particles making the LPM effect negligible. This effect is known as pre-shower. This effect reduces the shower to shower fluctuations of converted primary photons.
1.1.6 Hadronic Interaction

General-purpose hadronic interaction models used in high-energy physics (HEP), such as PYTHIA [23, 24], HERWIG [25] and SHERPA [26], are developed to interpret the data measured in accelerator experiments mainly related to hard-scattering measurements. Their emphasis is not on the bulk of hadron production at lower transverse momenta. The predictions of models can be adjusted by a large number of parameters used in these models to represent fundamental physics quantities, and to adjust phenomenological assumptions or simplifications. These models are typically optimized for processes that can be calculated in perturbation theory. Also the other assumptions needed for generating complete final states for hadronic interactions are often kept at a more simple level. Again, most of these models are mainly designed for proton, pion or photon interactions and therefore are not suited for nuclear interactions relevant for Cosmic Ray collisions with air nuclei in the upper atmosphere [27].

On the other hand, interaction models QGSJET01 [28], QGSJET-II [29, 30, 31] and sibyll [32, 33, 34] etc. used in cosmic-ray physics are supposed to predict hadronic interactions as realistically as to reproduce existing accelerator measurements and to provide a reliable extrapolation to energy beyond that. That is to generate phase-space regions where no data are available. There is typically only one “optimal” parameter set to make the prediction relevant to the production of high energy secondaries. Soft particle production are included in some more sophisticated models with more emphasis on the relation of the total, elastic and inelastic cross sections to particle production. Some other models such as PHOJET [35, 36], DPMJET [37, 38] and EPOS [39, 40], are more universal and meets the sophistication of HEP models regarding some aspects of hard $q-q$ and $q-\bar{q}$ processes. Once the parameters of these models are tuned to produce a large set of accelerator data at various energies, they can be used for different experiments also.

The basic feature of hadronic interactions is the distribution of the produced secondaries in phase space characterised by a uniform rapidity distribution and a steeply falling distribution of transverse momentum. Van Hove introduced the concept of the so called ‘longitudinal phase space’ [41], where the transverse momentum scaling of $\approx 200\text{MeV}/c$ is given by the Planck constant $\hbar$ divided by the radius of proton. Under Lorentz transformations the invariance of a uniform rapidity distribution implies that there exists no privileged momentum frame. To explain this behaviour Feynmann introduced the concept of partons to develop the field theory of elementary hadron constituents [42] and which were later identified with gluons. Quantum Chromodynamics (QCD), is the $SU(3)$ component of the $SU(3) \times SU(2) \times U(1)$ Standard Model of Particle Physics [43]. Ac-
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According to colour hypothesis, each quark flavour carries three strong colour charges, red ($R$), green ($G$), and blue ($B$). Colour singlet (colour-neutral) states of quarks exist as free particles. This leads to colour confinement and explains why free quark or states like $qq$, $q\bar{q}$ etc. can not exist. The quarks interact through a non-Abelian gauge field known as gluons which are self interacting. QCD reduces the strong interaction to essentially three Lagrangian terms associated with the bremsstrahlung-like radiation of gluons, either from a quark or from a gluon. The fundamental parameters of QCD are the coupling $g_s$ (or $\alpha_s = g_s^2/4\pi$) and the quark masses $m_q$. The strong coupling becomes weak for processes involving large momentum transfers (hard processes), $\alpha_s \sim 0.1$ for momentum transfers in the range $100\text{GeV} - 1\text{TeV}$. These Lagrangian terms are easily accessible to experiments that probe short distances, while their effects are hidden at large distances. Low transverse momentum interactions, those prevail in the development of extensive air showers, can only rely on the so-called “QCD inspired” approximate models [44].

Some of the properties of hadronic interactions could be explained in the late seventies and early eighties. For example, with experiment UA5 [45] in addition to the longitudinal phase space configuration, the slow increase with energy of the total cross-section, the existence of diffractive events, the existence of short range rapidity correlations, the existence of a leading effect are also known [46]. Leading effect means that the largest rapidity particle essentially carries the quantum numbers of the initial proton.

1.1.7 Hadron Component

An air shower is a combination of two different kinds of cascades, namely a hadronic and an electromagnetic cascade. Muon component in hadronic showers is significantly large, but there are very few muons in purely em showers. The hadronic cascade is mainly responsible for the energy transport within a shower. A simple model similar to the Bhabha-Heitler model, is useful for basic understanding of hadronic showers. It is assumed that a hadronic interaction of a particle having primary energy $E_0$ produces $n_{tot}$ new particles with energy $E_0/n_{tot}$ each. Ratio of charged particles (charged pions) $n_{ch}$ and neutral particles (neutral pions) $n_{neu}$ is 2:1. Neutral pions will decay immediately ($\pi_0 \rightarrow 2\gamma$). Charged particles will interact again with air nuclei if their energy is greater than decay energy $E_{dec}$, else decay. If $n$ is total number of generations of hadronic interactions, we have

$$E_0 = E_{dec}(n_{tot})^n \quad (1.7)$$
Assuming that one muon is produced in the decay of each charged particle, we have

\[ N_\mu = (n_{ch})^\alpha = \left( \frac{E_0}{E_{dec}} \right)^\alpha, \quad (1.8) \]

with \( \alpha = \ln \left( \frac{n_{ch}}{n_{tot}} \right) \approx 0.9 \). The numerical values of \( \alpha \) and \( E_{dec} \) depend on the muon energy threshold for different hadronic interaction models [47]. Thus number of muons produced is almost directly proportional to primary energy. The energy transferred to the em shower component in each hadronic interaction is assumed to \( 1/3 \)rd of the initial energy. After \( n \) generations the energy in the hadronic and em components is given by

\[ E_{had} = (2/3)^n E_0 \]

and,

\[ E_{em} = E_0 - E_{had}. \quad (1.9) \]

### 1.1.8 Muon Component

The atmospheric flux of muons and neutrinos originates from the decay of charged pions and kaons produced by cosmic rays in the atmosphere

\[ \pi^\pm \rightarrow \mu^\pm + \nu_\mu (\bar{\nu}_\mu), \quad 99.9\%, \quad \tau = 26\text{ns} \]

\[ K^\pm \rightarrow \mu^\pm + \nu_\mu (\nu_{\mu}), \quad 63.5\%, \quad \tau = 12\text{ns}. \quad (1.10) \]

Muons have a relatively large lifetime (\( \tau = 2.2\mu\text{s} \)) and decay as:

\[ \mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu, \]

\[ \mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu \quad (1.11) \]

Again low energy cosmic ray muons are influenced by the Earth’s magnetic field, through the process of magnetic rigidity cut-off of the primary cosmic rays penetrating the Earth’s atmosphere from the cosmos. It is obvious from the decay chains that the ratio of the number of positive to negative atmospheric muons, termed as the muon charge ratio \( R_\mu = \mu^+ / \mu^- \), is related to the neutrino production. Thus \( R_\mu \) carries vital information regarding hadronic interactions involved [48].
1.1.9 Čerenkov Radiation

When charged particles move faster than the phase speed of light in a medium with index of refraction $n$, i.e., $v > c/n$, they emit Čerenkov light. The characteristic angle is given by

$$\frac{1}{\cos \theta_c} = \beta n,$$

(1.12)

where $\beta = v/c$. Index of refraction $n$ is a function of the frequency $\nu$ of the emitted photons, $n = n(\nu)$. The spectral distribution of Čerenkov photons per path length of an emitting particle with charge $\pm Ze$ is given by

$$\frac{dN}{dx d\lambda} = \frac{2\pi z^2 \alpha}{\lambda^2} \left(1 - \frac{1}{\beta^2 n^2}\right),$$

(1.13)

where $\alpha$ is the fine structure constant. Multiplying Eq. 1.13 with energy of the emitted photons $E_\gamma = h\nu$ and integrating it over $\nu$, total amount of released energy per particle path length is obtained as

$$\frac{dN}{dx} = \frac{2\pi z^2 \alpha h}{c} \int_{\beta n \geq 1} \left(1 - \frac{1}{\beta^2 n^2}\right) d\nu.$$

(1.14)

Most of the particles in the shower disc travel with relativistic velocities through air. Approximately one third of the charged particles emit Čerenkov light [49]. The Čerenkov characteristic angle in air at sea level is $1.3^\circ$ only. Electrons in EAS have relatively low Čerenkov threshold (21MeV at sea level), hence they contribute mostly to the Čerenkov light associated with an air shower. In water the Čerenkov characteristic angle is $\beta = 41^\circ$.

1.1.10 Radio Emission

Coherent radio emission generated by extensive air showers by charge exchange mechanism was theoretically predicted by Askaryan in 1961 [50]. In 1965, it was experimentally discovered by Jelly et al. at a frequency of 44 MHz [51]. This phenomenon provides an alternative to traditional methods of detection of high-energy cosmic rays with energy greater than $10^{17}$eV. In the 1960s and 1970s the experimental and theoretical efforts in this direction had only limited success. Detection of radio pulses from EAS at 30, 44, and 60 MHz frequencies with the aid of wide band broad-side arrays of half-wave dipole antenna systems have been reported during 1970s and 1980s [52, 53]. Modern experiments, such as CODALEMA [54] and LOPES [55], are aimed at studying radio emission from air showers using modern and improved instruments. Antenna systems are being placed at
the site of the Pierre Auger Observatory in Argentina to investigate the possibility for
radio detection of air showers at the highest energies.

1.1.11 Fluorescence Radiation
At very high energy \((E > 10^{17}\text{eV})\) the fluorescence light technique can be used to observe
the longitudinal development of air showers directly. This technique is based on the
detection of fluorescence light emitted isotropically by nitrogen molecules that are excited
by charged particles due to the air shower traversing the atmosphere.

The ability to image the shower development directly is one of the advantages of the
air fluorescence technique. Fluorescence detectors make use of the fact that the charged
particles of the air shower cascade ionize air molecules and thus leave a trail of low-energy
electrons in their wake. These low-energy electrons excite air molecules that subsequently
fluoresce in the ultraviolet. Nitrogen is the most important component of atmosphere
responsible for air fluorescence.

There are two transitions of electronic states of the nitrogen molecule, known as 2P
and 1N states. In combination with the change of the vibrational and rotational states
of the molecule, this results to several fluorescence emission bands. Most of the energy is
emitted between 290nm and 430nm. The most prominent bands are centered at 316nm,
337nm, 357nm, and 391nm \([56]\). The lifetime of the excited states of nitrogen is of the
order of 10 ns and the fluorescence light is emitted isotropically.

The fluorescence yield, or the number of photons produced by a charged particle per
unit track length, depends on pressure, temperature, and humidity. It is approximately
3-4 photons per meter for MeV electrons in dry air at standard conditions.

1.1.12 Mass Composition Estimation
Mass of the shower-inducing primary particle can be estimated with the help of following
array observables–

i) the electron to muon number ratio,

ii) the arrival time distribution of the particles,

iii) the shape and width of Čerenkov pulse, and,

iv) the slope of the lateral distribution charged particle and Čerenkov radiation.

The shape of the shower front or the arrival time distribution of the particles at observ-
ational level are used estimate the mass sensitive EAS parameter, the depth of shower
maximum \(X_{\text{max}}\) indirectly. Considering Eq. 1.6 for protons and nuclei with mass number
A, and substituting energy $E_0$ with $E_0/A$ (adopting the superposition model),

$$X_{\text{max}}^A = X_{\text{max}}^p - X_R \ln A.$$ \hspace{1cm} (1.15)

where $X_R$ is the radiation length. Thus depth of shower maximum for iron induced showers should be $\sim 150\text{g/cm}^2$ less than that for proton induced showers. The predictions of the different models regarding the absolute values of $X_{\text{max}}$ are different. When the model predictions are compared with the experimental data to derive information about the elemental composition of primary cosmic rays, these differences play important role.

Measurement of the electron-to-muon ratio at ground level is the most commonly used composition estimator. According to Heitler cascade model, the ratio of electrons to muons at shower maximum can be estimated [57].

$$\frac{N_e}{N_\mu} \approx 35.1 \cdot \left( \frac{E_0}{1 \text{ PeV} \cdot A} \right)^{0.15}.$$ \hspace{1cm} (1.16)

Thus the ratio $N_e/N_\mu$ depends on the energy per nucleon $E_0/A$ of the primary particle. By deriving the energy of the shower inducing primary from another EAS observable, the mass can be inferred.

### 1.2 Monte Carlo Method

The Monte Carlo method is an application of the laws of probability and statistics to the natural sciences. In this method every sequential sub-process in a physical process is assigned to a distribution of random numbers. Monte Carlo methods are especially useful for simulating systems with many coupled degrees of freedom. The modern version of the Monte Carlo method was invented in the late 1940s by Stanislaw Ulam, while he was working on nuclear weapon projects namely the Manhattan project at the Los Alamos National Laboratory [58]. It was named, by Nicholas Metropolis, after the Monte Carlo Casino. Immediately after Ulam’s breakthrough, John Von Neumann understood the significance of the method. Neumann programmed the ENIAC(Electronic Numerical Integrator and Computer) machine to carry out Monte Carlo calculations [59]. Monte Carlo methods are mainly used in three distinct problems: optimization, numerical integration and generation of samples from a probability distribution.
1.2.1 The Method

The Monte Carlo method provides approximate solutions to a variety of mathematical problems by performing statistical sampling of experiments on a computer. In this method computer generated pseudo random numbers are used to simulate a physical process, which is divided into step by step procedures. Using a known probability distribution of the physical process at every step, the outcome is determined using random numbers. Thus in Monte Carlo simulation one generates many virtual or artificial events according to model selected with particular choices. These events may then be statistically analyzed to yield real observable parameters and compared with the existing real data. This method applies to problems with no probabilistic content as well as to those with inherent probabilistic structure. Monte Carlo technique is known as a method of statistical trials. A program is prepared for only one random trial of the experiment or event, and, repeated for \( N \) times. Each trial being independent, the average of all the trials will predict the net result. Again the error is proportional to \( \sqrt{K/N} \), where \( N \) is the total number of trials and \( K \) is a constant. Thus to have greater level of accuracy one has to lower the value of \( K \) by adopting suitable algorithm, decent computational technique and the subprocesses closer to the real event considered for simulation, rather than mere increase of the number of trial \( N \) \([60, 61]\).

1.2.2 Pseudo Random Number

Monte Carlo methods require large amounts of random numbers. As the result of advent of modern computer, the development of pseudo-random number generators comes into the picture, which are far quicker and easier to use than the tables of random numbers that had been previously used for statistical sampling. Random number generators consist of deterministic algorithms that produce numbers with certain predefined distribution properties. These sequences of so-called ‘random’ numbers are periodic and depend on the initial input, hence are called ‘pseudo-random number’. Multiplicative Linear Congruential Generators (MLCG) was first use in 1948 by D. H. Lehmar \([62]\). MLCGs are simple kind of random number generators to generate a sequence of random numbers with the help of simple recursion relation

\[
r_{i+1} = (ar_i + c) \mod m,
\]

(1.17)
here we have to provide a starting value known as seed. A sequence of random integer $r_i$ between $(0, m - 1)$ is obtained. Usually $m - 1$ is the largest possible integer that the machine can assign. Variable $a$ is the multiplier. Value of $c$ is either 1 or 0 depending on whether we need exact zero or not. The integer $r_i$ obtained with the help of Eq. 1.17 is then divided by $m$ to get random floating sequence in the range $[0, 1]$. Despite of wide use and simplicity, various defects of MLCGs have been pointed out. To overcome these defects, Compound Multiplicative Linear Congruential Generators (CMLCG) consisting of two or more MLCG are adopted where two or more seeds are exploited. To have the correct results in a simulation of a physical process with the use of random number generators, they have to pass certain tests that the user considers relevant for his problem. The difficulty with randomness is partly due to the fact that random variables are often mixed up with numbers. For example, the notion of independence is only defined for random variables, not for numbers. Good random number generators are characterized by theoretical support, convincing empirical evidence, and positive practical aspects. They have to produce correct results though not all, but in many simulations.

CORSIKA [63, 64] is operated with the random number generator RANMAR in the version as implemented in the CERN program library [62]. In this version slight modification to generate a vector of pseudo random number was done by F. James of CERN to the original version due to Marsaglia and Zaman [65]. It is a pseudo random number generator delivering uniformly distributed numbers. With the use of RANMAR, user can generate simultaneously up to $9 \times 10^8$ independent sequences. Each sequence can have a length of $\approx 2 \times 10^{44}$. The generator is written in standard FORTRAN-77 and, thus, portable to all types of computers where bit-identical results are obtained. It satisfies various tests regarding randomness and uniformity and it is sufficiently fast.

1.2.3 Probability Distribution Function

If the probability $P(x)$ of finding a random variable $x$ in the interval $[x, x + dx]$ is given by $P(x) = f(x)dx$, then $f(x)$ is said to be the probability density function of the variable $x$. The value of $x$ must lie within the interval $[-\infty, +\infty]$, the probability density function is normalised so that

$$\int_{-\infty}^{+\infty} f(x)dx = 1.$$ (1.18)
Again the cumulative distribution function $F(x)$ is defined as

$$\int_{-\infty}^{x} f(x) dx = F(x) \quad . \quad (1.19)$$

Now to construct a random variable $x$, to be distributed uniformly in a given range $[x_1, x_2]$, the probability distribution function can be expressed as

$$f(x) = \begin{cases} \frac{1}{x_2 - x_1} & \text{for } x_1 \leq x \leq x_2 \\ 0 & \text{otherwise} \end{cases} , \quad (1.20)$$

the random variable is sampled from

$$x_i = x_1 + (x_2 - x_1) r_{i} \quad , \quad (1.21)$$

where $r_{i}$ lie in the interval $[0, 1]$.

### 1.2.4 Rejection Method

For generating random numbers from a given distribution, we have to adopt some suitable and robust strategies known as sampling algorithm. The rejection sampling framework allows to sample from relatively complex distributions, subject to certain constraints. This method is used in event generation. To make a random variable $x$ to be distributed in accordance with a given probability distribution function $f(x)$, at first $x$ is chosen uniformly in the integration region $[x_1, x_2]$. Then we have to accept $x$ if

$$\frac{f(x)}{f(x)_{\max}} \leq r \quad , \quad (1.22)$$

or reject otherwise. Here, $r$ is uniform random variable in the range $[0, 1]$, and $f(x)_{\max}$ is the maximum value of $f(x)$ within the integration region $[x_1, x_2]$. The choosing of $x$ and performing the test inequality relation 1.22 are to be continued till accepted $x$ is found.

### 1.2.5 Transformation Method

Sometimes we require non-uniformly distributed random variable. A non-uniformly distributed random variable $x(r)$ can be constructed from an uniform random variable with range $[0, 1]$ by using transformation method (inversion technique). To generate a non-
uniformly distributed random variable $x(r)$, it is required that

$$P(r \leq \hat{r}) = P(x \leq x(\hat{r})),$$

$$\int_{-\infty}^{\hat{r}} g(r)dr = \hat{r} = \int_{-\infty}^{x(\hat{r})} f(x)dx = F(x(\hat{r})),$$

(1.23)

where $g(r)$ is uniformly distributed in the range $[0, 1]$. Here putting $F(x(r)) = r$, taking the inverse $x(r) = F^{-1}(r)$, the distribution $x(r)$ can be made in accordance with $f(x)$, which is non-uniform.

1.3 Motivation of this work

High energy phenomena related to nucleus-nucleus / hadron-nucleus interactions at high energy always attract and fill scientific community (experimental as well as theoretical) with enormous excitement. As a result, higher and higher energetic collisions are becoming feasible due to continuous and consistent advancement in collider physics and related technological advent. Now at LHC 7TeV p-p collisions become possible to uncover new horizon in physics [66].

On the other-hand, the cosmic ray since its discovery and its related phenomena, are providing another dimension in study regarding H.E interactions, even at U.H.E. region. Being the natural laboratory at above the energy attainable by present day man made accelerators, CR related phenomena are providing the supporting knots to the H.E interaction mechanism. So, studying the CR related phenomena, one can guess, infer, even argue about the complex processes that are taking place in the formation of EAS. Again due to very low statistics of such high energetic recorded events, simulation becomes inevitable. Here, the need of H.E. models comes into existence. Extrapolation to the available collider physics meets the need of detailed theoretical understanding of multi-particle production mechanism at H.E. in vivid ways in different models based on different theoretical frameworks. At present there is no theoretical model that can provide a consistent understanding of the reaction dynamics of heavy ion collisions over the whole energy range. At low and intermediate energies, descriptions in terms of hadrons (resonances) are appropriate, but, at high energies the quark and gluon degrees of freedom become important and dominate the mechanism. Simulation provides the bridge between the experiments and theory, and on the other hand, it serves as a tool to compare the differences in the outcomes from different models. Thus simulation may serve to
resolve conflicts between two representative models projecting two different frameworks by pinpointing the differences involved in the prediction regarding a particular observable or parameter. In this way, coherence among the models may be achieved, or better understanding of the related physics may be revealed.

In these above context, efforts have been made to figure-out some of the EAS related H.E. model dependent parameters, study on which may be helpful in the understanding of HE interactions.

1.4 Plan of the thesis

This thesis is an attempt to study some EAS signatures bearing information regarding some properties of primary cosmic rays using simulation. Again comparative study among different hadronic interaction models used in EAS simulation is done using simulation code CORSIKA. Here we have discussed the related theoretical concept in respect of pertinent different High Energy models. The organisation of this thesis is as follows:

Chapter- 1 contains the very general brief description about origin, energy spectrum, and, mass composition of primary cosmic rays. This is followed by the brief phenomenological description about Extensive Air Shower, Photon Electron Cascade, Electromagnetic-, Hadron-, Muon Shower, Čerenkov Radiation, Radio Emission and Fluorescence Radiation. In the second part, an overview on the Monte Carlo Method, Pseudo Random Number Generators including RANMAR used in CORSIKA air shower simulation code, Rejection Method, and Transformation Method are discussed.

Chapter- 2 contains brief description of different air shower simulation packages. Various prospects of simulation program CORSIKA, program structure, High Energy interaction models and low energy interaction models available in CORSIKA are also discussed in brief. An introduction to data analysis framework ROOT [67] is served. Application of ROOT in CORSIKA are also illustrated.

In Chapter- 3, brief descriptions about the High Energy hadronic interaction models are given. A comparative study is made for different hadronic interaction models used in CORSIKA in terms of high energy interaction parameters like cross-section, rapidity distribution, and transverse energy flow. These models are also tested with available data from accelerator.

In Chapter- 4, simulation is done for proton and iron primaries with primary energies from $10^{14}\text{eV}$ to $10^{19}\text{eV}$ using different high- and low-energy models. Optimum thinning options are selected to save CPU time. Longitudinal development of EAS, relation be-
between $X_{\text{max}}$ and elongation rate with primary energy, mass composition, H.E. models are studied. Various model predictions are compared with the data.

In Chapter-5, lateral distribution of electrons, muons, electron to muon ratio are studied for iron and proton primaries for different hadronic interaction models. Also model dependence on the energy spectra for muon and hadron with different threshold energies are examined.

In Chapter-6, relation of primary energy of the shower inducing particle with various EAS parameters namely shower size, muon number, electron to muon content ratio, hadron content etc. are studied with simulated data for different H.E. models.

Chapter-7 contains comparison of H.E interaction models EPOS-1.99 and QGSJET-II-03 using CORSIKA-6990 in terms of various EAS parameters.

Summary and future perspectives are presented in Chapter-8.
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