Chapter 2

Current status of the Cosmic Ray Knee

2.1 Introduction

At energies above 10^{14} eV, direct measurements of cosmic rays are not possible because of its very low flux following a power law spectrum. Therefore, while at energies below 10^{14} eV the large flux allows direct measurements by sending small detectors on balloon flights and artificial satellites, above 10^{14} eV, use of large arrays of ground based detectors for many years of exposure is the only way to study and extract informations about the primary cosmic rays. By acquiring information about the secondary particles produced by the interaction of primary cosmic rays with the atmospheric nuclei the results of such indirect way of measuring cosmic rays depend on the understanding of high energy interactions in the atmosphere. Different methods have been employed by several experimental groups on the basis of results obtained from Monte Carlo simulation codes for EAS, upgraded by their authors to extract information about the cosmic ray primary.

The experimental status of the cosmic ray knee and its theoretical explanations are discussed below.

2.2 Review of world wide experimental data

First the detection of the knee in the shower size spectrum was done by the MSU experiment [3, 4]. There after several cosmic ray air shower experiments detected the knee feature. Several studies have been performed over last six decades in the knee region to derive primary energy spectrum of cosmic rays and its composition. The past air shower experiments mostly derived all-particle energy spectra from their measurements. However, modern experiments obtained the energy spectra for groups of elements in the PeV region have from indirect measurements too. Systematic studies were done to compare the effect of hadronic interaction models used in simulations in order to reconstruct the primary energy spectrum from EAS.

As mentioned before, the cosmic ray energy spectrum extends up to 10^{20} eV with a knee at energy around 3 PeV. Below the knee region, the spectrum is obtained by satellite based experiments like PROTON [35, 36], SOKOL [45–47] and balloon flight based experiments like JACEE [57, 58] and RUNJOB [61, 62]. Fluctuations in these kind of experiments are very high because of the smaller detection area. Above the knee region, experiments like Haverah Park [70], Fly's Eye [71, 72] and HiRes–MIA [73] have been performed. These experiments are ground based with an objective of determining the energy spectrum above knee with primary composition. In the knee region, various ground based experiments at different altitudes, such as Akeno (1984, 1992) [74, 75], EAS-TOP (1999) [76, 77], CASA-MIA (1999) [78, 79], DICE (2000) [6], BLANCA (2001) [80], HEGRA (2000) [81], Yakutsk (2001) [82], GRAPES-3 (2001)[83], BASJE (2004) [84], KASCADE (2005) [85] and Tibet (2008) [86] have been performed with different methods. These experiments are summarized in the table 2.1.

Here, only the experiments in the knee region are discussed. Based on the type of detectors used, these experiments can broadly be divided into 3 categories which are briefly discussed below.

2.2.1 Experiments using particle detectors only

The energy spectrum of the cosmic rays between $10^{14.5}$ eV and 10^{18} eV was studied by Akeno air shower array [74, 75]. With 150 scintillation detectors and 9 stations of proportional counters, electromagnetic and muon components of EAS were detected. The primary energy spectrum was derived form electron size spectrum using the longitudinal development curve observed at mount Chakalatya. A knee can be seen at energy $10^{15.67}$ eV at which the spectral index is 2.62 ± 0.12 below and 3.02 ± 0.05 above. No further significant change in the slope of electron and muon size spectrum is seen beyond $10^{15.67}$.

CASA-MIA [78, 79] detectors included 1089 surface particle detectors (CASA) , spaced 15 m apart over a square grid and 1024 underground muon detectors(MIA) at the Dugway Proving grounds, south-west of Salt Lake City, Utah at an altitude of 870g cm^{-2}. The goal of this experiment was to study the cosmic ray energy spectrum in th energy range 10^{14} eV to 10^{16} eV. The MOCCA [87] shower simulation program, using the SIBYLL [88–90] hadronic interaction model was used for the event generation purpose [78]. The differential shower size spectrum obtained from this experiment clearly shows a kink around $10^{5.8}$ particles. A change in the spectral index from 2.69 to 3.12 can be seen at energy $10^{15.5}$ eV which is shown in the table.

The BASJE-MAS [84] array is located at an altitude of 5200 m above seal level at Mt Chacaltaya. With its 68 unshielded scintillation detectors and one shielded detector, it measures the showers with energies around the knee region near their maximum development. Because of this the shower size at maximum, $N_{e_{max}}$, is independent of shower development fluctuations and/or different primary composition. The calculation of energy spectrum is done by comparing the equi-intensity curves for various zenith angle bins with the simulated ones with five primary components and using CORSIKA [91, 92], a 3-D air shower simulation program, with the QGSJET [93–95] model.

The KASCADE [85] experiment was situated at an altitude 110 m above sea level. With an array of electron and muon detectors, a central hadron calorimeter with substantial muon detection areas and a tunnel with streamer tube muon telescopes, it is claimed to be one of the most precise air shower experiments in the world. After the shower reconstruction, the all particle spectrum and spectra for elemental groups [96–100] derived from electromagnetic, muonic and hadronic components are compiled with CORSIKA [91, 92], using QGSJET [93–95] and SIBYLL [88–90] hadronic interaction models. A rigidity dependent cut-off was observed in the analysis of these spectra.

The GRAPES-3 [83] high density air shower array is designed for the studies of extensive air showers near the knee. It is located at Ooty at an altitude 2200 m above sea level. With its 721 scintillation detectors and 16 muon stations it performs multi information studies on electromagnetic and muon components of EAS. Two small muon telescopes are used below the scintillation detectors for calibration. The primary energy spectrum is derived by compiling CORSIKA simulation. The results are shown below in the table.

The Tibet air shower array [86] was designed to perform studies on EAS as well as high energy celestial gamma rays. It consists of 761 scintillation detectors which spreads over an area of 36, 900 m^2. The primary energy of each event is derived from the shower size N_e which is calculated by fitting the electron densities with NKG function. The all particle energy spectrum is derived comparing the experimental data with CORSIKA [91, 92] simulation with QGSJET01c [93–95] and SIBYLL2.1 [88–90] interaction models. Several kinds of mixed composition models were used, namely QI, QHD, QPD, QP and SHD [86] in order to analyze the data. A distinct knee can be observed in the all particle spectrum. However, the main uncertainty with the primary composition is not resolved because of the unavailability of muon data.

2.2.2 Experiments using photon detectors only

Each of the the two DICE [6] telescopes, located at the CASA-MIA [78, 79] site in Dugway, Utah as described before, consisted of a 2 m diameter f/1.16 spherical mirror with a focal plane detector of 256 close packed 40mm hexagonal PMTs which provided $\sim 1^o$ pixels in an overall field of view $16^o \times 13.5^o$, centered about the vertical and are separated by 100 m. The collected data were analyzed by comparing with simulated events from CORSIKA [91, 92]. A sharp knee was observed around 3 PeV in the all particle energy spectrum derived from this analysis.

The Yakutsk [82] array in Siberia is one of the most complex array which covers an area of 18 km^2. Along with 58 ground-based and 6 underground scintillation detectors, it was designed to study cosmic rays between energies 10^{16} eV to 10^{18} eV. Also 35 photomultiplier systems were installed to study Cerenkov radiation associated with air shower. Currently the array has been rearranged to cover an area of 10 km^2 so that detailed study of EAS can be made around 10^{19} eV. The change in spectral index from 2.7 to 3.12 can be observed around 3 PeV.

2.2.3 Experiments using both particle and photon detectors

The EAS-TOP [76, 77] experiment, located at 2000 m above sea level at Campo Imperatore, Italy performed multi-component studies of EAS in the energy range between 10^{14} eV and 10^{16} eV using electromagnetic, muon, hadron and Cerenkov detectors. The results are shown in the table. The proton spectrum obtained from hadrons agrees well with the extrapolation of the direct measurements [101]. The Cerenkov data combined with MACRO muon data is normalized to the proton + helium flux of direct measurements and the results obtained are compatible with the extrapolation of the direct measurements [102].

The AIROBICC Cerenkov array and the scintillation detector matrix of the HEGRA [81] air shower complex was located at a height of 2200 m above sea level and covers an area of $180 \times 180 m^2$. 243 plastic scintillation huts of the detector matrix and 49 open photo multiplier tubes(fitted with Winston cones) of the AIROBICC array were used to derive a spectrum for the proton and helium component together as well as an all-particle spectrum [103] between 0.3 PeV and 10 PeV. CORSIKA [91, 92] simulations were used for event reconstructions. A knee can be seen in the all particle spectrum(normalized to the extrapolation of direct measurements below 1 PeV) as well as in the combined spectrum of proton and helium.

CASA-BLANCA [78–80] detectors included 144 angle-integrating detectors (BLANCA [80]) with an average separation of 35 to 40 m which recorded the lateral distribution of air shower Cerenkov light along with 957 scintillation counters (CASA [80]) for the detection of particles. The Cerenkov measurements were compared with CORSIKA [91, 92] simulations with EGS4 [104] and GHEISHA [105] codes within the energy rage 0.3 to 30 PeV. Several hadronic interaction models like QGSJET [93–95], VENUS [106], SIBYLL [88–90], and HDPM [91] were used for the extrapolation of available particle data. The observed all particle spectrum shows a smooth knee around 2-3 PeV primary energy.

The results of these experiments are given below in the table 2.1.

TABLE 2.1: Status of the CR experiments and the knee. γ_1/γ_2 are the spectral indices for the energy spectrum below/above the estimated knee energy($\mathbf{E_{knee}}$).

Name of the Experiment	**Detector Type**	**Simulation Model/ Particle Type**	γ_1	$\mathbf{E_{knee}}$ **(PeV)**	γ_2	$\mathbf{E_{range}}$**/GZK (PeV)**
PROTON(1970)	Particle	–	2.62	–	–	0.001–0.1
Akeno(1984-1992)	Particle	–	2.62±0.12	5	3.02±0.03	1.0–630
SOKOL(1993)	Particle	Proton All	2.85±0.14 2.68±0.07	–	–	0.0025–0.005
Fly's eye(1994)	Photon	–	–	–	3.01±0.06	200–3200
JACEE(1995)	Particle	Proton Helium	2.86±0.07 2.72±0.09	–	–	0.002/n–0.04/n 0.002/n–0.06/n
EAS-TOP(1999)	Particle & Photon	–	2.76±0.03	2.7–4.1	3.19±0.06	0.9–10
CASA-MIA(1999)	Particle	MOCCA	2.66±0.02	1.0	3.00±0.05	0.1–10
DICE(2000)	Photon	–	–	3	–	0.2–15
HEGRA(2000)	Particle & Photon	–	2.72±0.02	3.98	3.22±0.47	0.3–10
CASA-BLANCA(2001)	Particle & Photon	–	2.72±0.02	2.0	2.95±0.02	0.5–10
Yakutsk(2001)	Photon	–	2.63±0.03	3.0	3.12±0.02	1.0–10
HiRes-MIA(2001)	Photon	–	–	–	3.07±0.11	100–2500
BASJE-MAS(2004)	Particle	QGSJET	2.66±0.00	3.16	3.19±0.02	0.1–10
RUNJOB(2005)	Particle	Proton Helium	2.74±0.08 2.78±0.20	–	–	0.01/n–0.5/n
KASCADE(2005)	Particle	QGSJET SIBYLL	2.70±0.01 2.70±0.06	4.0±0.8 5.7±1.6	3.10±0.07 3.14±0.06	1–100
GRAPES-3(2001–Present)	Particle	QGSJET SIBYLL	–	–	–	0.03–30
Tibbet(2008)	Particle	QI QHD QPD QP SHD	2.81±0.01 2.67±0.01 2.65±0.01 2.60±0.01 2.67±0.01	4.4±0.1 4.0±0.1 3.8±0.1 3.4±0.1 4.0±0.1	3.21±0.01 3.10±0.01 3.08±0.01 3.03±0.01 3.12±0.01	0.1–100 0.1–100 0.1–100 0.1–100 0.1–100

2.3 Theoretical models of the knee

There are several theoretical models modelling the knee in the cosmic ray spectrum. They can be broadly categorized into two groups. The first category of models consider the knee as an intrinsic property of the energy spectrum where as the authors of the second category of models consider new type of physics processes/interaction in the atmosphere as the source of the knee. In other words the first category of models consider the knee to be astrophysical in origin whereas the second category describes the knee as an effect of the extensive air showers in the atmosphere.

Some of the models of the first category relate the knee with the acceleration of cosmic rays by supernova explosions and its several extensions [5, 15, 23, 24, 108]. Recent studies show that magnetic field is amplified by SNR which confines cosmic rays more effectively to the shock region, thus resulting more efficient acceleration [109]. Thus this amplification of magnetic field accelerates cosmic rays to PeV energies in supernova remnants. A source related model [18–20] is there which considers a nearby single source as a primary source of cosmic rays. Models like re-acceleration of cosmic rays by spiral shocks in the galactic wind [110] and acceleration of comic rays by the ejected matters in the galactic halo [111, 112] were advanced to explain the knee. Diffusive shock acceleration of the cosmic ray particles with energy dependent path length [6] and diffusive propagation of cosmic rays in the galaxy [7–10] are also proposed as the origin of the knee in the primary energy spectrum. Some other models consider interaction of the cosmic ray particles with background photons [11–14] or the neutrino background [113] as the cause of the knee. Diffusive propagation with photo-disintegration [16, 17] also proposed as the origin of the knee.

The models of the second category consider the knee as a result of creation of new particles during the development of air shower which is not seen in the modern day experiments. These models argue that the energy is transferred into technihadrons [21] or gravitons [22] which can not be observed by air shower experiments. Also since the energy threshold of these interactions is in the knee region which is above the collider experiments, it is not observed there too.

Some of these theoretical models are discussed below.

2.3.1 Acceleration in supernova remnants

Based on the diffusive propagation of cosmic rays in SNRs, Berezhko and Ksenofontov [15] in their work explained that the energy of cosmic ray particles is increased significantly because of their repeated crossings of the shock front which in turn modifies the planar nature of the shock front. This generates a power law spectrum of cosmic rays which is altered because of the modification in shock wave due to the hardness of spectrum. A minimum velocity is required to cross the shock wave front, that determines the injection rate of the particles. It is believed that the injection efficiency is related to the mass to charge ratio (A/Z) of the nucleus considered. So heavier elements are expected to accelerate more efficiently. Considering pre-acceleration in the wind of the predecessor star, the maximum energy achieved is $Z \times 10^{15}$ eV. The resulting all particle energy spectra is found to have a knee due to the charge dependence of the maximum energy achieved in the acceleration process.

2.3.2 Acceleration by supernova shocks

Stanev et al. [5], based on the concept of particle acceleration in the shocks where shock normal is perpendicular to the prevailing magnetic field, proposed that the energy spectrum of cosmic rays is consisted of three components. The first part is formed by protons with a spectral index of 2.75 which are accelerated up to the energy 10^5 GeV by the blast waves, generated from the explosions of supernovae into an approximately homogeneous interstellar medium. The second part of the spectrum is formed by the particles with energy up to 3×10^9 GeV (heavier elements and rigidity dependent) which are produced because of the explosions of stars into their former stellar wind. It has a spectral index 2.67 up to rigidity dependent bend in the spectrum and 2.97 up to rigidity dependent cut-off. The last and extragalactic part is formed by the particles with even higher energies, up to near 10^{11} GeV produced in the hot spots of $Fanaroff$ *Riley class* II radio galaxies with a spectral index -2 up to the pileup just below the cut-off due to the interaction with the cosmological microwave background.

This model argues that shocks that travel down a steady stellar wind with spiral magnetic field accelerate the main fraction of galactic cosmic rays above about 10 TeV. The shock normal is assumed to be perpendicular to the magnetic field except around the poles where direction of propagation of the shock is parallel to the magnetic field which results a harder spectra for the accelerated particles. Thus polar cap has a very little contribution towards the spectrum up to 10 TeV while from 10 TeV to the knee, polar cap contributes appreciably. At knee energies, polar cap begins to contribute significantly, almost equally in comparison with rest of the hemisphere, resulting a sharp bend in all particle spectrum. So the logical outcome from this model is the change in composition of the all particle spectrum around the knee region since the fluxes of nuclei are different according to their charge Z.

2.3.3 Acceleration by oblique shocks

In this model, Kobayakawa et al. [108] used slightly modified version of the diffusive acceleration of particles in supernova remnants where magnetic fields are at arbitrary angles to the velocity of shock front. The basic idea is based on the fact that particles are accelerated to higher energies in oblique shocks as compared to parallel shocks. The shape of shock fronts, generated because of the ejected material from a supernova explosion that expands into the interstellar medium, are supposed to be almost spherically symmetric. The directions of the interstellar magnetic field lines is considered to be random rather than well aligned. It is assumed that the field lines meet the shock front at random angles and the cosines of these angles are distributed uniformly. The injection efficiency into the acceleration regime is believed to be a function of the angle between the magnetic fields and the normal of the shock front. It also makes the spectrum harder. The spectra generated by this model shows a rigidity dependent knee.

2.3.4 Acceleration by a variety of supernovae

Based on the recent astronomical observations of supernovae, Sveshnikova [23, 24] proposed a new approach which is a slightly revised version of the standard approach of cosmic rays acceleration in shock fronts of supernovae. This new approach gives us a scenario in which the maximum energy reached in SNR acceleration is the knee energy and depends on three factors, the charge Z of the nucleus, strength of the magnetic field B and density of protons in the interstellar medium and on the energy of explosion as well as the velocity of shock.

2.3.5 The single-source model

Erlykin and Wolfendale [18–20] in their model considered a single nearby source as an additional source of cosmic rays because of which a two-kink structure related to the cut-offs of oxygen and iron nuclei from the single source is supposed to be seen in the cosmic ray energy spectrum. They used shower size spectra (normalized to the knee position) to show the two fold structure. After re-binning the normalized shower size spectra a twofold structure in the all-particle spectrum at 3×10^6 GeV and 10^7 GeV was seen. But the structure at 10^7 GeV is yet to be observed in the all particle spectrum obtained from the present day experiments.

2.3.6 Re-acceleration in the galactic wind

Volk and Zirakashvili [110] proposed that galactic wind, mainly driven by cosmic rays and hot gas generated in the disk, reaches supersonic speeds at about 20 kpc above the disk, and is assumed to be very extended (several 100 kpc) before it ends in a termination shock. Also the galactic rotation leads to strong internal wind compressions, bounded by cosmic ray shocks that re-accelerate the most energetic particles from the disk by about two orders of magnitude in rigidity which ensures a continuation of the energy spectrum beyond the knee up to the ankle. The maximum energy achieved by this process is

$$E_{max} = Z \times 10^{17} eV \tag{2.1}$$

which concludes that the knee in the all-particle spectrum is intrinsic in nature , i.e. a feature of the source spectrum itself.

2.3.7 The cannonball model

Based on the model discussed by Dar and De Rujula [114] to explain the gamma ray bursts, Plaga [111, 112] proposed a mechanism for the acceleration of the cosmic ray hadrons in which he investigated that masses of baryonic plasma (cannonballs), ejected in bipolar supernova explosions, could be the universal sources of the hadronic galactic cosmic rays. It is assumed that the total cannonball energy is converted to the energy of the cosmic ray particles in order to match the observed cosmic ray flux. The two scenarios for the acceleration are ultra-relativistic shocks in the interstellar medium which can accelerate the cosmic rays up to the knee energies and second-order Fermi acceleration inside the cannonballs. Energy spectra for groups of elements, derived from this model show a knee which is proportional to the charge with a soft change in the spectral index. The obtained all particle spectrum which is dominated by light particles in the whole energy range is in reasonable agreement with the average measured flux.

2.3.8 The minimum-pathlength model

Swordy [6], based on Leaky Box model for the cosmic ray propagation, proposed that the knee is a consequence of leakage of particles from the galaxy. It is assumed that the spectra of particles accelerated by diffusive shocks have the same spectral slope for all elements at the source with a rigidity dependent cut-off above which the spectra decreases. The path-length for escape from the galaxy which is a function of the galactic radius is assumed to decrease with rigidity but has some minimum value. The energy spectra is calculated by taking the fractional abundances and using the average all particle spectrum as obtained from many experiments. A smooth change in the spectral index can be seen in the individual spectra calculated from this model.

2.3.9 Anomalous diffusion in the Galaxy

Lagutin et al. [7, 8], using fractal geometry as a description of interstellar medium and the magnetic field, proposed that the knee structure is due to the anomalous diffusion of the cosmic rays in the magnetic fields of the galaxy. The large free paths of the cosmic ray particles in the magnetic field domain are considered to be the results of this anomaly and can not be explained with normal diffusion process for their propagation. The spectrum is considered to be formed of two parts. The first part between energies 0.1 Gev to 10 GeV is considered to be formed by the numerous distant sources where as the higher energies region are formed by the contribution from near by sources, including 16 supernova remnants. The energy spectra for individual elements obtained from this model show a very smooth behaviour in the knee region, no kink in the spectra is visible and no distinct energy for the knee can be specified. The all particle spectra, derived from this model, shows a very smooth change of the spectral slopes.

2.3.10 Photo-disintegration and diffusion

Several authors have considered that the knee is due to the interactions of cosmic rays with various background particles. Based on the idea of Hillas [115, 116], photo-disintegration of nuclei in a dense field of photon is considered one major process which results the knee. Cosmic rays are considered to be accumulated near the source because of the magnetic field and therefore interacts with photons on their pass across the photon field. Photo-disintegration process along with the leakage of cosmic rays from the galaxy by diffusion process in the galactic magnetic field are considered for the explanation of the knee. Authors like Karakula [16] and Tkaczyk [17] considered that the cosmic ray particles, following a power law spectrum with a spectral index of 2.75 for protons and 2.55 for all other nuclei up to iron, interact with the photon background having a Planck type distribution.

The energy loss processes, like pair production, pion photo-production on nucleons, and photo-disintegration of nuclei were taken into consideration. Assuming the galactic magnetic field to be dominated by its turbulent component, trajectories of particles were calculated starting at random positions inside the galactic disk. The leakage of cosmic rays from the galaxy is also taken into account. The knee, in the region between 1 and 30 PeV in the all particle spectrum is explained by the photo-disintegration of nuclei and due to leakage.

2.3.11 Neutrino interactions in the galactic halo

Dova et al. [113] considered that the knee is due to the interaction of cosmic rays with massive neutrinos in the galactic halo. Significant increase in the average number density of standard model neutrinos with mass m < 1 MeV due to gravitational clustering in galaxies and a magnetic dipole moment of massive neutrinos are considered to explain the increase in the cross-section for the inelastic scattering of nucleons on the neutrino background. Considering a cosmic ray spectrum with a spectral index 2.8 and having 60% protons and 40% iron, the propagation is described by a diffusion model, taking into account the galactic magnetic field. The calculated spectra for the proton and iron are found to be in agreement with the measurements. But this model overestimates the flux of light elements above the knee.

2.3.12 Nucleophysical Process in atmosphere

The basic idea behind this model is that a new type of interaction transfers energy to particles which are not yet observed in air shower experiments. These interactions start at the knee region which is above the energy of today's collider experiments. Kazanas and Nicolaidis, in this model proposed that the energy is transferred into techni-hadrons [21], the lightest super symmetric particles, and gravitons [22]. A single power law primary spectrum with spectral index 2.75 is assumed. It is considered that at energies above knee, a fraction of protons interact with this new type of interaction whose cross-section increases with increase in energy and particles like techni-hadrons and gravitons were formed which can not be observed by the modern day experiments. The spectrum calculated by this model shows some deviation from observed spectrum.