Chapter - 1

GENERAL INTRODUCTION ON COSMIC RAYS

1.1 Cosmic Rays :

Since the discovery of the Cosmic rays (CRs) by Victor Hess[1] in 1912 studies on its various aspects have provided a good deal of information on a range of diverse fields extending from high energy physics to stellar evolution. CRs, comprising mostly of charged particles, span more than 13 decades of energy ($\sim 10^{7}$eV - 10^{20}eV) with an energy spectrum of the form $F(E)dE \propto E^{-\gamma} dE$. Below 10 GeV the spectrum is affected by solar activity as well as by geomagnetic fields and hence the spectrum is time dependent. Accelerators, hitherto devised in the laboratories, can accelerate particles only upto an effective energy of $\sim 10^{14}$eV. Therefore above this energy CRs are the only source of super high energy particles.

The origin of the CRs is still a current problem of great interest. Various models [Ginzburg and Syrovatskii[2], Hillas[3]] have been proposed to explain the origin, acceleration and confinement of the CRs within the galaxy. However a model which could describe the generation, propagation and confinement of most of the CRs observed near the earth has not yet been established. Galactic and meta-galactic models on the origin of the CRs have been proposed depending upon the location of the CR sources. In the meta-galactic models the CRs are thought of as flowing into the galaxy from the meta-galactic region. The disk model and the halo model are the main galactic models of CR origin. In these the sources are conceived of as being confined to the galactic disk and the trapping region is a gas disk whereas it is a quasi-spherical halo in the latter case. At higher energies ($> 10^{18}$eV) the galactic models seem to fail and extra-galactic CRs from the local super cluster have been shown to be compatable with the present observations on CR anisotropy, however the power of the sources required was severe.

The nature of the sources of the CRs whether these are entirely discrete or diffuse is still controversial. Baade and Zwicky(4) in 1934 first suggested supernovae as the discrete sources of CRs owing to the availability of enormous energy in such explosions. Later on Fermi(5) in the year 1949 suggested the alternative diffuse origin of CRs, accelerated stochastically by collisions with waves throughout the interstellar medium. According to him such a process could produce the observed power law energy spectrum. But problems associated with (i) feeding the wave energy to the interstellar medium, (ii) the high efficiency of acceleration required, (iii) the enrichment of CR nuclei of $Z > 2$, lead to a drift back to the supernovae as the source of CRs. Ginzburg and Syrovatskii(2) in the year 1964 have prescribed a discrete origin of CRs in the supernovae. But still it was not solved fully, the most important problem perhaps was that the single power law energy spectrum observed from about 10^{10}eV to at least 10^{15}eV seemed to require a single source as no fundamental process would give the same power law spectrum in every discrete source and power law spectra from many sources with any dispersion in the spectral index would not sum to give a single power law spectrum. Soft X-ray and UV observations (reviewed by McCray and Snow[6]) depicted that a major fraction of the interstellar space is filled with a hot ($T \sim 10^6$ °K), tenuous ($n \sim 3 \times 10^{-3}$/cc) gas phase - a phase interpreted [Cox and Smith[7], McKee and Ostriker[8]] chiefly as a coalescence of many supernovae remnants which are thoght to fill more and more of the interstellar space and thus both the ideas of discrete supernovae and diffuse interstellar medium origins have now been synthesized into a single model along the lines suggested by Blandford and Ostriker[9] and such an origin seemingly mingles the best of both worlds with the supernovae energy being transferred by the shock waves to accelerate the CRs throughout the interstellar medium causing thereby a single power law energy spectrum.

Since most of the CRs are charged particles their direction of motion gets continuously changed by the interstellar magnetic fields in their journey from the source to the earth's surface. Consequently they arrive isotropically at the earth's surface. Hence one can have direct knowledge about the CR sources and their distribution within the galaxy or beyond the galaxy by studying on the neutral components that survive from the point of their production to the place where they are detected. The neutral components are neutrinos and gamma rays.

1.2 Direct Measurements on Cosmic Rays :

Direct measurements on the composition and energy spectra of CRs have been carried out by making use of a variety of satellite or high altitude balloon-borne detectors. The highest energy observed is of the order of a few TeV. It may be possible to extend the energy range to 100 TeV in the near future /Muller,[10] Vernov et al.,[11] Burnett et al.,[12]_7. However, above these energies low flux and limitations of the weight of the space-bound detectors as well as their exposure time make the direct measurements on CRs impracticable.

1.3 Indirect Measurements on Cosmic Rays :

In the energy range above 10^{14}eV all the informations regarding the primary CRs are to be obtained indirectly through studies on the Extensive Air Shower (EAS) because the properties of EAS depend upon the high energy particle physics as well as on the nature of the primaries producing the EAS particles. In the earth's atmosphere the primary CR particles interact and give rise to cascades of secondary particles, the conglomeration (shower) of particles being known as the extensive air shower (EAS). The secondary particles (in the shower) are studied at a given altitude (usually at sea level or at mountain altitude) to derive some aspects of the primary CR particles. It is to be noted that the secondary CR particles, being at many generations removed from the primaries, dilute the informations carried on by the primaries.

1.4 Extensive Air Shower (EAS) Phenomena :

A primary CR particle of high energy ($>10^{14}$eV) arriving at the top of the atmosphere undergoes nuclear collisions with an air nucleus and transfers nearly half of its energy to the numerous secondary particles produced. In bulk the secondaries produced are pions while the rest are kaons, nucleon-antinucleon pairs and may be some heavier flavours like charm, or even some exotic particles. Some of the pions and kaons decay in flight while the rest including the surviving psimary particle undergo further interactions down in the atmosphere and thus successively produce more and more particles as they move down the atmosphere. Pions decay into muons and neutrinos while the decay products of kaons include pions, muons, electrons and neutrinos. Since the muons and neutrinos do not interact strongly their paths in the atmosphere are merely straight. The neutral pions sum approximately to one-third of the total pions and they decay into high-energy gamma rays which ultimately develop into copious electron-photon cascades, generally known as the 'soft-cascades.' The shower develops as the particles multiply and the process of multiplication continues till there is enough energy available. Henceforth the atmosphere acts as an absorber and the particles lose their energy through the process of ionization. So we see that the number of particles in a shower increases initially, reaches a maximum and then diminishes because of attenuation.

In a broad sense the EAS can be divided into three components viz., the electro-magnetic component, the muon component and the hadronic component. In addition to these the relativistic particles also produce the optical Cerenkov radiation, radio emission and the isotropic fluorescent light.

1.4.1 Electromagnetic Component :

Neutral pions generated in the hadronic collisions undergo spontaneous decay into two high energy gamma rays which then initiate the electron-photon cascades developed through the process of pair production, bremsstrahlung and Compton scattering. The superposition of all these cascades constitutes what is known as the electromagnetic component of the shower. Because of multiple Coulomb scattering the shower particles spread laterally to hundreds of metres. The central region around the projected axis of the incoming primary CR particles is known as the core of the shower. The density of the shower particles is maximum at the core while it falls off rapidly as the distance from the core increases.

1.4.2 Muon Component :

Muons in EAS do not interact strongly and so they merely reach the observational level straight from the point of production. They are the most penetrating particles and only a few of them decay into electrons (or positrons) and neutrinos during flight. They bear generic informations from various stages of longitudinal development of EAS. Particularly the high energy muons due to their origin in the early stages of shower development carry information from the highest energy interactions in the cascade. Because of their non-linear dependence on shower size or primary energy, muons are also the most sensitive component to the primary composition. The arrival time structure of muons at large core distances can also yield informations on the longitudinal development of the shower. Except muons and neutrinos all other shower partjicles are absorbed within a few metres of the earth's crust.

1.4.3 Hadronic Component :

Hadrons in EAS render direct information on high energy interactions. They consist of nucleons, anti-nucleons, charged pions and kaons. Though this is the least abundant component of the shower but on an average hadrons carry substantial amount of the energy of the primary CR particle and thus form the backbone of the shower. It is very difficult to study this component of the shower both at distances near the core of the shower as well as at distances far away from the core. Near the core the interference from the electromagnetic component is very large while at distances far away from the core the density of hadrons is very low because of the steep lateral distribution and of small hadron-content in the shower ($\sim$1% of the shower population). It is to be noted that this component feeds energy continuously to the other components of EAS.

A detailed study of this component associated with showers of different size-ranges has been done by various workers[13-16]. These observations depict that the hadron energy spectrum is characterised by a power law form with an exponent varying between -1.2 and -2.0 and its lateral distribution has an exponential form flattening as the shower size increases. Time structure of hadrons in air showers has been studied by TIFR[17] and Maryland University[18] groups. These studies render informations on high energy interaction characteristics as well as on the primary composition.

In recent years Matano et al.,[19] operated their SYSEAS array with an air shower trigger instead of triggering on burst size in scintillators under 15 cm of lead absorber to reduce bias effects. The properties of the hadronic component as found by them were (i) lateral distribution was steeper for younger showers, (ii) average burst size decreased with shower age etc. Aseikin et al.,[20] analysing their data on the extremely energetic hadrons obtained at Tien Shan found that the average energy of energetic hadrons per shower particle decreased from (19 ± 1.7)MeV/el at $N=10^4$ to (12 ± 2)MeV/el at $N=8.9 \times 10^4$ which can be explained on the assumption of an increase of the average inelasticity with energy at around 3×10^{13}eV. The Maryland group[21,22] has presented preliminary results from their sea-sevel experiment on the hadronic energy flow and low energy delayed hadrons and has compared with preliminary Monte Carlo simulations and has shown that the hadronic component is sensitive to primary composition. However sensitivity of the hadronic component to the interaction model is still to be studied. Dybovy and Nesterova[23] made an interesting analysis on EAS hadron energy spectra as a fraction of primary energy E_h/E_o in showers of size $(1.5 - 3.6) \times 10^5$ [E_o =400-900TeV] measured in the Tien-Shan experiment to obtain the primary composition. Comparing the experimental spectrum with calculations (using rising cross sections and violation of scaling in the central region and different models of composition) and then normalising the two at $E_h/E_o \lesssim 2 \times 10^{-3}$ where the hadron number is insensitive to the primary composition they concluded the primary nuclear composition consisting of $\gtrsim$30% protons and $\sim$ 20% α- particles.

1.4.4 Cerenkov Radiation in Extensive Air Showers :

Electrons and positrons above a certain threshold energy radiate Cerenkov photons, mostly in the visible region, during the propagation of the shower through the atmosphere. The threshold energy depends upon the refractive index of the medium. The lateral spreading of the Cerenkov photons is quite large and they undergo little absorption in a clear sky. The Cerenkov light is linearly polarised. The most conspicuous and unique feature of this component of shower is its pulse profile at large distances from the core ($\sim$300m). This phenomenon is significant in regard to the longitudinal development of the shower and thereby to the primary mass number and high energy interaction characteristics. In addition, the total number of photons in the shower is nearly proportional to the integral track-length of the electrons and positrons and hence is a good measure of the primary energy.

Pioneering work in this field of EAS was made by Galbraith and Jelley[24] and since then considerable progress has been attained by various workers. The phenomenon of Cerenkov radiation in showers and early observations on it have been reviewed by Boley[25] and Jelley[26]. Recent survey on this field has been performed by Rao[27]. The quantitative relation between the depth of shower maximum and Cerenkov pulse profiles, lateral structure of Cerenkov photons etc has been shown to be independent of primary mass and high energy interactions models [Fomin & Khristiansen[28], Protheroe and Turver[29] and Kalmykov et al.,[30]]. In recent years, Chantler et al.,[31] reported measurements on the time delay between the Cerenkov light front and the particle front and prescribed that this parameter is sensitive to the depth of maximum and is particularly useful for small showers for which the time delay is expected to be large.

The main drawback of observing the Cerenkov radiations in EAS lies in its very method of detection. The observations are to be carried out only during the dark, clear and moonless nights. Further the atmospheric absorption and scattering dilute the parameters to be measured remarkably. Hence it becomes essential to carry out the observations at almost identical atmospheric conditions. All these constraints restrict the observational period to barely 5-10% of the year.

1.4.5 Other Components of EAS :

The macroscopic displacements of electric charges, chiefly due to the geomagnetic deflections, that occur during the development of the shower result in the creation of the electric dipole moments which give rise to radio emission. The radio pulses from EAS were first detected by Jelley et al.[32] A detailed discussion on this aspect of EAS has been made by Allan[33]. Radio frequency spectrum and lateral distribution of field strength have been studied in showers initiated by primaries of energy $>10^{16}$eV. Lateral distribution of the field strength has been studied in the core distance range 30-300m while the frequency spectra obtained lay in the frequency range 0.1 MHz to 100 MHz [Allan et al[34], Atrashkevich et al[35], Clay et al[36], Baggio et al[37] Barthakur et al[38], McDonald and Prescott.[39]].The contribution to the radio emission from the geo-electric field becomes dominant during thunderstorms and therefore raises serious problems about the validity of the informations obtained by the radio-technique [Mandolesi et al.,[40] and Allan[41]].

Extensive observations on the radio frequency pulses emitted from the EAS have been made by many workers with the hope that it would trace the longitudinal development of the shower as well as its primary composition. The depth of the shower maximum was found to be correlated with the lateral distribution of the radio frequency pulses. However like Cerenkov radiations reliable data can be collected only during fair atmospheric conditions as well as electrically undisturbed periods. Therefore due to these constraints the contribution from this component of EAS in understanding the primary composition becomes fairly meager.

At very high energies ($> 10^{18}$eV) the detection probability of EAS with the help of nitrogen flurescence light is very promising (Greisen[42]). The emitted radiation is highly isotropic and thus very infrequent and very high energy showers could be detected over a very large detecting area ($\sim$a few hundred sq.km.). As in the case of Cerenkov radiation measurements the detection of optical fluorescent photons is restricted to only 5-10% of the year. Only preliminary results from the 'Fly's eye' experiment that studied the profile of the atmospheric scintillation light has been reported so far [Cassiday et al.,[43]].

1.5 Results from EAS Studies :

Studies on EAS become very much complicated because of the fact that most of the parameters observed depend on high energy interaction characteristics as well as the primary composition both of which are unknown. Hence conclusions about one depend highly on the assumptions regarding the other.

The important interaction characteristics, relevant for the development of showers are the interaction cross-section, multiplicity of various kinds of secondary particles and its distributions, distributions of the longitudinal and transverse momenta of the secondary particles, distribution and average value of the inelasticity and the energy dependence of all these parameters. Information on both the characteristics of high energy interactions and the primary composition are to be inferred still from the studies on EAS. Hitherto it has not been possible to disentangle the effects due to these two aspects through a study on the average behaviour of the shower parameters. Attempts have been made by several workers to find out ways of separating the effects due to high energy interactions from those due to the presence of the heavy primaries but with little success. Studies on the fluctuations and correlations of some of the components of the shower have proved fruitful and have reduced the above confusion. Various results regarding the primary CRs from recent shower experiments have been summarised by Sreekantan[44], Linsley[45] and Hillas[46].

1.5.1 Primary Composition :

Regarding the primary composition one can only specify it in broad terms such as predominantly protons or predominantly heavy nuclei or the mixed composition and often the composition obtained even in such qualitative terms depend largely upon the model of high energy interaction characteristics assumed. However several workers have inferred primary composition by various methods of studying EAS, a discussion of which has been made by Sreekantan.[47]

Results on the composition of the primary CRs have been obtained by studying the variation of the electron density near the shower core, core structure (multicore showers), time structure of hadrons, energy spectra of the leading hadrons, fluctuations in energy flow of high energy hadrons, fluctuations and lateral distributions of muons as a function of shower size, lateral distribution of Cerenkov light, pulse profile and full width at half maxima of the Cerenkov pulses, fluctuations in Cerenkov light etc in EAS. Results obtained by hadron and Cerenkov light obsergations favour (at$\sim 10^{15}$eV) a composition which is predominantly heavy, while those based on muons favour, in general, the normal mixed composition. Recent review on the composition of the primary CRs in the light of observations on the Cerenkov light has been given by Rao[48]. It has been pointed out that absorption and scattering of photons due to Rayleigh and Mie scattering processes have been ignored in calculations so far. The effect of scattering is shown to be considerable by Protheroe.[49]

1.5.2 Anisotropy Measurements :

The subject of anisotropy of the CRs has been well reviewed by Wolfendale[50], Kiraly et al[51] and recently by Lloyd-Evans and Watson[52]. The directional distribution of the CRs has been studied in the wide energy range 10^{12}eV to 10^{20}eV and the results depict that siderial anisotropy is present at levels that exceed noise over most of the range. From these observations it has been depicted that the extent of anisotropy is a function of the particle energy as well as the declination. Again the feature of the anisotropy appear to be correlated with the features of the spectrum. The harmonic analysis of the distribution of showers in the right ascension (RA) at different energies depicts that the amplitude of the first harmonic is constant ($\sim$ 0.05%) upto an energy of 10^{14}eV beyond which it increases with energy, approximately as $\sqrt{E}$ upto the highest energy. The phase of the maximum is found to change from (212 $\pm$ 17) RA to (30 $\pm$ 19) RA between 10^{17}eV and 10^{18}eV. There seems to be an evidence for an enhancement of the CRs in the energy range 5 x 10^{17}eV - 10^{19}eV from Southern galactic latitude, mainly from the direction of spiral out and near South galactic pole. Also there is a tendency for the CRs of energy $> 10^{19}$eV to arrive from the Northern galactic latitudes, from the direction of Virgo cluster for example.

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