CHAPTER I

HISTORICAL INTRODUCTION

I.1 The discovery of cosmic radiation.

The first observations that led ~~to~~ ultimately to the discovery of cosmic rays were made in 1900 by C.T.R. Wilson (1) and by Elster and Geitel (2). Independently they observed that an electroscope in a vessel at earth potential gradually lost its charge by the motion of gaseous ions produced by a small residual ionization even if it is very carefully insulated. An ion current can only be maintained if the ions, which are swept away by the electric field, are constantly replaced by new ones. The assumption that the ions are produced by some internal mechanism as, for example, by thermal agitation, was rejected as improbable, and it was concluded that the ionization must be due to some outside agency such as x - rays or γ - rays.

Later investigations by Rutherford and Cook (3) and by Melennan and Burton (4) in 1903 showed that the rate of ionization in a closed vessel is considerably reduced when it is surrounded by a sufficiently thick layer of lead or other absorbers. This proved that the "penetrating radiation" as it was then called, comes partly from outside the ionization chamber.

In 1909 a large number of investigations on the conductively of gases and its causes followed. Wulf (5) and Gockel (6), as a result of the analysis of their own results and those of others, came to the conclusion that the whole of the penetrating radiation can be accounted for in terms of γ - rays emitted by radioactive substances present near the surface of the earth.

Pacini (7) in 1912, who observed simultaneous variations of the rate of ionization on high mountains, over a lake, and over the sea, did not accept this conclusion. He concluded that a certain part of the ionization must be due to sources other than the radioactivity of the earth or the air.

It was many years, however, before the origin of this source of ionization was shown by Hess (8) to lie outside of the earth. Hess employed free balloons to carry ionization chambers to altitudes about 5,000 m. above sea-level and found that at these heights the ionization is already two or three times that observed at the earth's surface. This discovery ruled out the possibility that the penetrating radiation is due to the radioactivity of the earth's crest and proved that it travels downward through the earth's atmosphere.

The result of Hess were later confirmed by Kolhorster (9) (1914 - 19) in a number of balloons flights up to 9,200 m. above sea-level. An increase of the ionization up to ten times that at sea-level was observed.

It was estimated that the cosmic rays coming from above were responsible for the production of 1 to 2 ion pairs per c.c. per sec.

The ionization at sea-level is mainly due to cosmic rays. Hess also found that the intensity of the radiation is practically the same at night as at the day time, and that its penetrating power greatly exceeds that of any other known radiations.

In 1922 Millikan (10) and his collaborators investigated by containing recording instruments in free balloons, and was thus able to obtain measurements at altitudes of 15,500 m.. In addition, observations were made in airplane flights and on mountain tops as well as at considerable depth in the water of mountain lakes. The existence of the penetrating radiations under all these conditions was confirmed, and since they appeared to come from an extraterrestrial source, Millikan in 1925 called them "cosmic rays"

I.2 Components of cosmic ray particles.

The earth's atmosphere is thus under the continuous bombardment of high energy particles coming from outer space. These particles are the primary cosmic rays occuring in the universe, accelerated by some unknown mechanism to be of great energy of the order of billions of electron volt per nucleon. The primary cosmic radiation consists mostly of protons (about 85%), alpha-particles and a small amount of heavier nuclei..

As they penetrate into the atmosphere, primary cosmic rays lose energy and gradually disappear on colliding against the oxygen and nitrogen atoms of the air. A nuclear reaction occurs and several new particles are created. These new particles are called "Secondary cosmic rays". In these collisions they collide with the nuclei thus producing secondary protons and neutrons. They also generate pi-mesons. The pi-mesons are known to be 276 electron masses. They may be positive or negative or neutral, and have zero spin. These are unstable and decay into a mu-meson and a neutrino.

$$\pi^{\pm} \longrightarrow \mu^{\pm} + \nu$$
$$\pi^{-} \longrightarrow \mu^{-} + \bar{\nu}$$

Neutral pi-mesons disintegrate immediately into two photons, which then multiply into showers.

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

The mean decay time τ_o for a pi-meson at rest is about 2.6×10^{-8} sec. If it moves with relativistic velocity, the time must be

$$\tau = \frac{\tau_o}{\sqrt{1 - \left(\frac{v}{c}\right)^2}}$$

where v = the velocity of pi-meson

c = the velocity of light

The mean free path before decay is

$$L = \tau v = \frac{\tau_o v}{\sqrt{1 - \left(\frac{v}{c}\right)^2}} = \tau_o \frac{P}{M_o}$$

where P is the momentum and Mo is the rest mass. For a pi-meson of 10^9 ev. energy one obtains L = 55 m. It is understandable, that very few pi-mesons are observed at sea level.

On the other hand the mean life of mu mesons at rest is longer than that of pi-mesons (τ: 2.15 x 10^{-6} sec.) Mu-mesons of 10^9 ev. have the mean free path before decay about 6 km. Again they are unstable and may decay into an electron and two neutrinos.

$$\mu^{\pm} \longrightarrow e^{\pm} + \nu + \bar{\nu}$$

Since the interaction with nuclei is weak, the mu meson productions in high altitudes directly or by decay of pi-mesons, is able to reach sea level without decaying or being absorbed by nuclei.

Thus it can be pointed out that the cosmic radiation, in general, consists of two main components, soft and hard when they are classified by the penetrating power.

a. Soft and hard components.

The extraordinary penetrating power of cosmic rays is shown, by their ability to pass through the earth's atmosphere, in the first place. A study of the absorption of cosmic rays in matter has shown the fact that the intensity does not decrease regularly with the thickness of the absorbing material. For example, with lead as absorber, as done by Rossi, (22) the intensity of the cosmic rays diminishes rapidly for the first 10 cm. thickness, and then falls off much more slowly. This indicates that the cosmic rays consists of at least two different types of radiation. That part which is absorbed by about 10 cm. of lead at sea level is called the "soft component" of the cosmic rays. It consists chiefly of electrons, positrons, gamma photons, and perhaps low-energy mesons. The portion of the cosmic radiation which is capable of penetrating much greater thickness of matter, and which is absorbed only with difficulty, is called the "hard components", consists of protons, pi and μ-mesons at high altitudes, and at sea level almost entirely of mu mesons. The soft component is more easily absorbed then the hard component in passing through the atmosphere. Since atmospheric absorption is equivalent to the absorption of ten meters of water, or one meter of lead, the soft component cannot be a primary cosmic ray constituent. Where the hard component is more closely related to the primary cosmic radiation. The soft component would not be observed at sea level, but it can still be detected at great depths below sea level. It may be explained by the fact that the soft component is equivalent to the secondary radiation resulting from the interaction of the primary rays with matter, or from spontaneous changes undergone by the hard component. The electrons of the soft component of cosmic rays are believed to orginate chiefly in three ways. Firstly, charged pi-mesons decay into mu-mesons and the latter than emit electrons, either positive or negative according to the sign of the primary mesons. Secondly, the decay of neutral mesons is accompanied by the liberation of gamma-ray photons of high energy which can produce positron-electron pairs when they collide with atomic nuclei, and, finally, result from direct impact of the fast mesons with the orbital electrons of the oxygen and nitrogen atoms in atmosphere.

b. Nuclear Interaction Components of Cosmic Rays.

As stated before cosmic rays contain many different kinds of particles, though not all of them may be able to produce "nuclear interactions" with a target nuclei. From experimental results of many investigators we concluded that protons, neutrons, and π-mesons are mainly responsible for this kind of interactions. It is probable that all of these particles have large nuclear cross-sections. This is known to be true for protons and neutrons with energies of the order of 10^8 ev. The prompt nuclear absorption of negative pi-mesons at rest show that these particles interact strongly with nucleons, and recent experiments have supplied convincing evidence that fast pi-mesons are very effective in producing nuclear interactions.

The relative number of nuclear interactions due to protons, neutrons, and pi-mesons, depend not only on the nuclear cross-sections of these particles, but also on their relative abundance in the atmosphere.

Most of the particles that cause nuclear interactions are of secondary origin and their abundance in the atmosphere is determined by their rate of production and by their rate of disappearance. Neutrons disappear only by nuclear interactions. Protons, lose energy by ionization. Pi-mesons disappear rapidly by spontaneous decay as they travel in the atmosphere and most mesons will decay before undergoing nuclear collisions.

Among the products of nuclear interactions, the following particles have been identified: protons, neutrons, heavier nuclear fragments, pi-mesons, photons (from the decay of neutral mesons), possibly K-mesons and hyperons and other kinds of short-lived particles. There are reasons to believe that pi-mesons have a cross-section for nuclear interactions comparable with nucleons. So that when a nuclear interaction occurs in condensed matter, secondary pi-mesons may interact again.

$$\pi^- + P \text{ (in nucleus)} \longrightarrow n + \gamma$$ [illegible]

$$\pi^- + P \longrightarrow n + \pi^0 \longrightarrow n + \gamma + \gamma$$

When a nuclear interaction occurs in air, the secondary nucleons are more effective in the production of further nuclear interactions than the secondary pi-mesons, because most of the pi-mesons decay into mu-mesons before undergoing a nuclear encounter.

When a nuclear interaction occurs, resulting sometimes are called cosmic ray stars. The star was interpreted as a nuclear explosion subsequent to the absorption of the mesons at rest (presumably a negative meson) by a nucleus of one of the elements in the emulsion.

Most of the negative pi-mesons give rise to stars at the end of their tracks in the emulsion. It appears likely that all negative pi-mesons produce nuclear disintegrations after coming to rest in the emulsion but that in about 27 per cent of the cases the nuclear disintegrations result in the emission of neutron only, and for the star producing by nuclear absorption of mu-mesons is very rare event.

I.3 Altitude Variations of Cosmic Rays.

1. Cosmic - ray Intensity at Various Altitudes.

The discovery of the existence of a radiation coming from the outer atmosphere, was made through observations of the intensity of radiation at various altitudes. The pioneering balloon flights of Hess (11) and Kolhorster (12), who attained respective altitudes of 5,200 and 9,000 meters, contributed some evidence regarding the manner of the increase of intensity of cosmic rays with altitudes.

Later in 1923 Millikan and Bowen (13) sent up small sounding balloons carrying sufficient recording apparatus to obtain the data at higher altitudes ~~were attained in this way~~. Four duplicate instruments were designed especially for the flights. Each of these included a recording electroscope and a recording barometer and a thermometer. The records were made on a moving photographic film driven by clockwork, so that the instrument is self-recording. These instruments were carried up by balloons similar to those used for weather observations. Each instrument was carried by two balloons. It was hoped that if one had broken at a high altitude, the other would carry the instrument back to earth. Three of the four instruments were recovered after the flight, and two of these had satisfactory records. These had attained altitudes of 11,200 and 15,000 meters, respectively. In agreement with previous work, these experiments showed that the intensity increases with altitude. But the increase was not as large as it appeared from the pioneering work of Hess and Kolhorster (11-12). The average intensity between 5 and the 15 kilometer levels was about three times that at the earth's surface. These general findings were confirmed shortly through measurements made on the top of mountains and in airplanes. After that, observations on the change of intensity with altitude have been carried practically to the top of the atmosphere. With the improved apparatus that later became available a more careful and detailed examination of the effect of altitude has been made at several different geomagnetic latitudes. The intensities obtained for cosmic - ray particles by the instruments are plotted against the corresponding values of the atmospheric pressure expressed in terms of meters of water, a pressure of 1 atm., or 76 cm. of mercury, being equivalent to 10.33 meters of water.

Results of studies at two places for instance, Madras & San Antonio are shown in Fig. I because of certain significant difference. Madras in India is very close to magnetic equator, 3° N magnetic latitude, whereas the place San Antonio in Texas is much farther north, 35° N magnetic latitude. From Figure I we see that these intensity - altitude ~~caves~~ curves are different. Although each has the same general form, and each reaches a maximum intensity

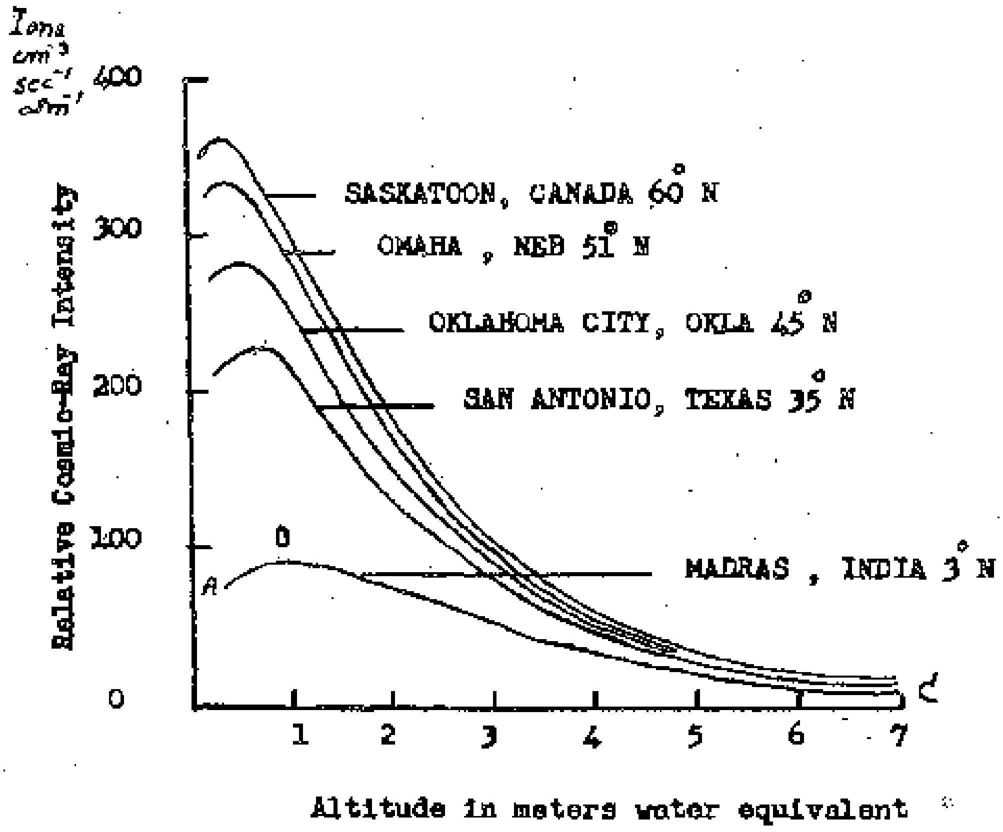


Fig. I Cosmic-ray intensity as a function of the atmospheric pressure.

(from : Source Book On Atomic Energy by Samuel Glasstone p 560) about 15,000 meters, above which the intensity starts to fall off with increasing height.

The general shape of the intensity-altitude curve may be explained in the following manner. Near the top of the atmosphere, the primmary cosmic ray particles, believed to be nuclei but mostly protons intereact with the molecules of oxygen and nitrogen in the air, producing numbers of secondary particles, mostly electrons, both positive and negative, and photons. The instrument which measures the total number of charged particles, of total ionization, thus registers an increase of intensity with decreasing altitude. This accounts for the small rising portions of the curves at the left of Fig I thus from A to B. As the secondary particles pass down through the atmosphere, they are absorbed, that is, they are slowed down until they no longer produce innization. Hence, as the instrument descends, the ionization intensity recorded decreases at first rapidly, and then more slowly as sea level is attained at the extreme right of the figure from B to C.

The latitude effect as shown in Fig I may be explained by different charges of the cosmic ray particles. The primaries of cosmic rays are electrically charged and are therefore deflected by the magnetic field of the earth while far outside the earth's atmosphere. A particle of mass m and charge e, moving with a velocity v perpendicular to a magnetic field H will describe in a circle of some radius ρ . If all quantities are expressed in the same system of units the relation

$$Hev = \frac{mv^2}{\rho}$$

holds for the quantities involved. The mass m is of course, the actual mass of a particle having a velocity v, it might be replaced by the quantity $m_o / \sqrt{1 - \beta^2}$ where m_o is the rest mass. If this equation is solved for the momentum of the particle one obtains

$$P = mv = eH\rho$$

where P is the momentum of the particle.

Charged particles approaching the earth from the zenith at the magnetic poles experience negligible magnetic deflections, so in this regions particles of all energies can reach the earth atmosphere. Particles approaching the earth at other latitudes, must cut across the magnetic field lines and are deflected as indicated in Fig 2. The deflections are greatest at the magnetic equator, but at every magnetic latitude θ, a charged particles approaching from the zenith must possess a minimum momentum in order to reach the earth's atmosphere. For relativistic particles with total

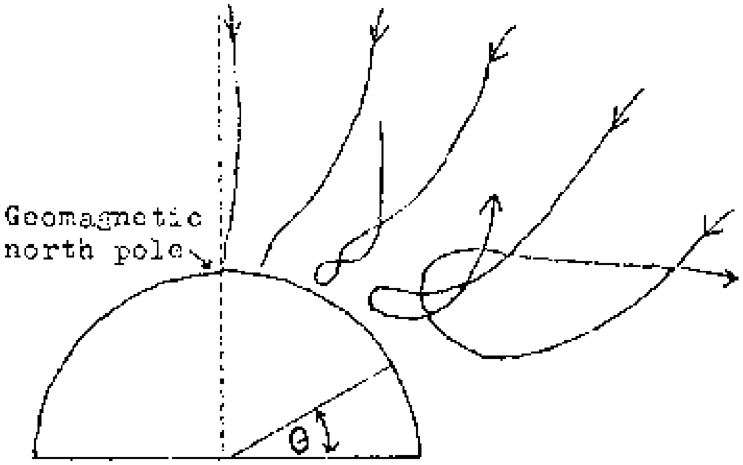


Fig. 2. Trajectiones of Primary Cosmic Rays in Earth's Magnetic Feild.

energy much greater than their rest energy, this minimum momentum is

$$P \text{ min.} \approx 14.8 \cos^4\theta \quad \text{Bev}/c \;\ldots\ldots\ldots\ldots\ldots\ldots\;(1)$$

Equation (1) implies that the cosmic - ray intensity should increase steadily from the equator to the magnetic poles. This does not occur because of absorption of the lower energy particles in the earth's atomsphere. As a result the intensity at each altitude increases to a critical latitude and then remains nearly constant to the magnetic pole. However, investigation of the latitude effect with free balloons at very high altitudes has revealed a steady increase in primary cosmic - ray intensity right up to the north magnetic pole. This proves that the cutoff of the primary cosmic - ray spectrum occurs at low energy. An important consequence of this fact is that the permanent dipole magnetic field of the sun must be small, since this magnetic field would tend to prevent low-energy cosmic - ray primaries from reaching the earth at all latitudes.

At each geomagnetic latitude, primary cosmic - ray protons must possess the minimum momentum given by equation (1) in order to reach the earth from the zenith. Greater momentum is required to penetrate the earth's magnetic field from directions other than the vertical. If the particle approaches in the east - west plane and at an angle ϕ from the zenith, then the limiting values of momenta needed for positive particles to reach the earth at magnetic latitude θ are

$$P_W = 59.3 \frac{\mathrm{Cos}^4\theta}{\left[1 + (1 + \mathrm{Sin}\phi\mathrm{Cos}^3\theta)^{\frac{1}{2}}\right]^2} \ \mathrm{Bev}/c$$

$$\ldots\ldots\ldots\ldots\ldots \quad (2)$$

$$P_E = 59.3 \frac{\mathrm{Cos}^4\theta}{\left[1 + (1 - \mathrm{Sin}\phi\mathrm{Cos}^3\theta)^{\frac{1}{2}}\right]^2} \ \mathrm{Bev}/c$$

The orbits of electrically charged particles in the field of a magnetic dipole were studied by Störmer (14) and after developed by Lemaitre and Vallarta (15). It was found that particles of any momentum can reach the poles of the earth but only particles of sufficiently high momentum can approach the earth at lower altitudes or at the equator. The minimum momentum for a singly charged particle to reach the equator in a vertical direction is found to be 15,000 mev/c and only particles of momentum exceeding 60,000 mev/c can reach the earth from any direction.

The effects produced by the magnetic deflexion of primaries may be termed geomagnetic effects.

Effects at High Altitudes due to Latitude

As mentioned before the cosmic-ray intensity has been measured up to considerable heithts with instruments carried up in balloons and aeroplanes. The latitude effect increases with height and at a height corresponding to 3 cm. of mercury pressure, it is about 80 per cent increase.

The latitude effect extends only up to geomagnetic latitudes of about ± 50°. For higher geomagnetic latitudes the intensity remains constant.

Cosmic Ray Stars.

The first extensive observation on the multiple nuclear disintegrations or "stars" produced by cosmic rays were made by Blau & Wambacher in 1937. They found that photographic plates kept for sometime showed "stars" i.e. groups of tracks originated from the common centre recalling those in Wilson chamber, but reduced in proportion to the greater density of the photographic plate compared with the gas in the chamber. Nuclear emulsion method is one of the 7 or 8 methods used in observing and measuring cosmic rays. All methods of detection depend on the ionization phenomena and the effects of collision process by charged particles. Thus the charge particles of cosmic ray can only be detected directly but neutral particles can only be detected indirectly through the intermediary of the secondary charged particles produced on their ways through matter.

Nuclear emulsions consisting of silver halide crystals mixed with gelatin placed on glass plates can record the trajectory of ionizing particles which pass through it permanently. Roentgen's and Becquerel's initial investigations were based on the blackening of the photographic plates by charged particles. The production of a few hundred ions in the neighbourhood of a silver halide grain in the emulsion renders the grain developable. When a large number of such events have occurred in a small region of a plate, that region is blackened in the development process. Ordinary emulsions contain only a small amount of silver compared to the other component present. With recent development of emulsions containing over 80 per cent silver halide by weight, however, the sensitivity is much increased, and under microscopic examination of the developed plate, the path of each ionizing particle appears as a track of silver grains.

The term "star" will be used to denote an event in which two or more heavily ionizing tracks appear to diverge from a common point in the emulsion, while "shower" will be used to denote one in which three or more lightly ionizing tracks do so. Tracks estimated to have a density of ionization one to three times minimum (minimum = the grain density of high energy electron which is about 12.5 grains per 50 microns) are classes as "light track" those of four times minimum or more as "heavy track". At high altitudes events with both light and heavy tracks are common. The term "shower-star" will be used when both two or more heavy tracks and three or more light tracks are present.

Some of the stars were due to contamination and represented successive α- particle disintegrations due to a speck of radioactive impurity in the plates. But others included tracks too long to be due to any known radioactive impurities. Furthermore, Stetter & Wambacher (16) in 1938 - 9 showed that the number of stars increased if the plates were taken for a few weeks to the top of a mountain. This was correctly interpreted as meaning that they are due to some component of the cosmic rays and represent fragments from the exploding nucleus of some atom in the emulsion.

For the event such as "stars", the following notations are commonly used.

The size of a nuclear disintegration which is also refered to as a "star" on "shower" observed in the emulsion is represented by

$$N_p + N_s \cdot X$$

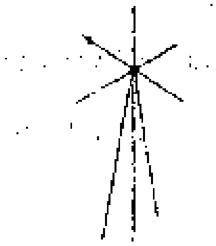
N_p = the total number of grey and black tracks with grain densities $>$ 1.5 minimum value.

N_s = the number of "shower particles" with grain-densities $\leq$ 1.5 minimum value

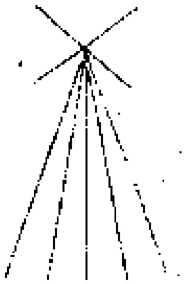
and X = is the type of primary particle producing the star.

The primary particle is represented by p for protons, α for alpha-particle and n for neutral particles.

The suffix 'p' is usually used when the track of the primary particle producing the disintegration is seen. If no such track is visible the event must be assumed to be produced by some form of neutral particles and the suffix 'n' used. Thus the following stars are denoted by

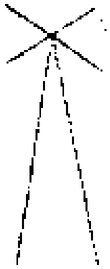


4 + 3p

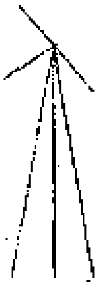


4 + 5n

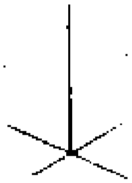
4 + 1p



4 + 2n



3 + 3n



4 + 0p

The interpretation is

4 + 3p = 4 prongs star produced by an incident charged particle probably proton (p) with three shower particles.

4 + 5n = 4 prongs star produced by neutral particle (not visible) with 5 shower particles.

4 + 0p = 4 prongs star produced by an incident charged particle but no shower etc. (175).