CHAPTER II

THE NATURE OF COSMIC RAYS

2.1 Origin of Cosmic Rays.

From the experiments it is found that the cosmic rays hit the earth all the times and in all directions. The energy of the primaries is so extremely high that the annihilation of heavy nuclei and the ordinary fission or fusion cannot produce such high energy particles. Furthermore these particles are accelerated by some unknown mechanism to high energy, which are in the range up to 10^{18} ev. (4).

It is postulated that there are three sources of the cosmic radiation. These sources are; the solar system, the Milky Way galaxy, the other galaxies.

1. The Solar System. Since there is diurnal variation of cosmic radiation, the sun may be responsible for part of cosmic rays. However, from the fact that the diurnal variation is very small(5), it is thought that the sun is not the main source, but after the detailed studies of Van Allen belts (6), (7), it was found that the belts behave as a leaky bucket or a splash catcher, with the particles continuously leaking to the earth or being accelerated to the earth all the times from the belts. These belts make the diurnal variation less. The diurnal change should therefore come only from the neutral particles. Because it is

found that the peak intensities of cosmic rays can occur only during the activity of the sun, this is the reason why the sun is the source of the particles.

2. The Milky Way Galaxy. In order to explain the extremely high energy of primaries, Fermi (8) considered the very fast ions in our galaxy. It has been known that the galaxy contains inhomogeneous magnetic field, which may arise from the rotation of the galaxy. The charged particles are assumed to be partially trapped within the galaxy and accelerated through the operation of the local variation in the field. The particles will move from the region of low field to the large magnetic field in helical orbit around the lines of force. These particles sometimes may be reflected back and be trapped in the field. The magnetic field may cause an increase or decrease in the energy. Some particles may attain very high energy and may move into the earth's atmosphere.

3. The Other Galaxies. If our own galaxy can produce high energy particles, then we can assume that the other galaxies will accelerate high energy particles and send them to our galaxy and such particles may pass through the earth.

2.2 Particle Interaction.

When primary cosmic radiations reach the atmosphere, some can reach the ground, but some produce electromagnetic and nuclear reactions in the atmosphere. The important electromagnetic processes are elastic scattering, excitation, ionization, bremsstrahlung, Compton effect, pair production and cascade shower. The most important of the electromagnetic reactions is the cascade shower. This process can be initiated by either a high energetic electron or photon, and at the end many low energy photons and electrons are produced. In this process, the electron produces photon by bremsstrahlung, and the photon produces electron and positron by pair production. During that time the average energy per particle decreases.

Nuclear reaction process also is very important in cosmic rays. The nuclear reaction makes the particles at sea level different from the primaries. One of the example is shown in Fig.1

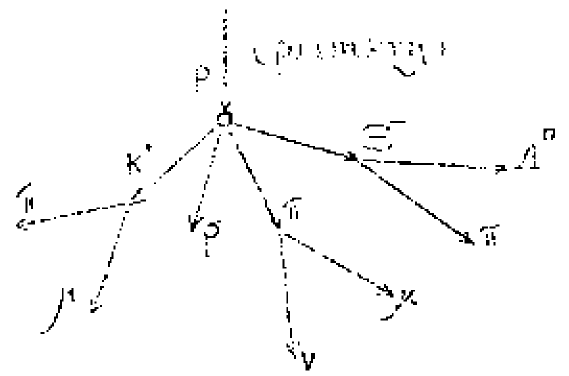


Fig 1 The Nuclear Reaction of Cosmic Rays

From such reactions many unknown elementary particles are found. Examples of the interactions (13) are as follows:

$$p + p \rightarrow K^+ + K^+ + p + p \, ,$$

$$\text{or} \rightarrow \Xi^- + \bar{K}^0 + K^0 + 2\pi^+ + p .$$

Sometimes primary cosmic ray particles can reach the earth without collisions with nuclei of gases in the atmosphere to produce secondary particles (Fig.1). These secondary particles usually decay with very short life time. For example, K^{+}, which is the product of the proton-proton interaction, can decay into several modes with mean life time of 1.22×10^{-8} second.

These decay modes are as follows:

$$K^{+} \rightarrow \mu^{+} + \nu \qquad 59\%,$$
$$\rightarrow \pi^{+} + \pi^{o} \qquad 27\%,$$
$$\rightarrow \pi^{+} + \pi^{+} + \pi^{-} \qquad 6\%,$$
$$\rightarrow \pi^{+} + \pi^{o} + \pi^{o} \qquad 2\%,$$
$$\rightarrow \mu^{+} + \pi^{o} + \nu \qquad 4\%.$$

Another product of the p-p interaction is K^{o}. The mean life time of K^{o} is 10^{-7} second. $\bar{K}$ and $\bar{K}^{o}$ decay in an identical manner to K^{+} and K^{o} , with the appropriate anti-particles as decay products. The modes of the decay are as follows:

$$K^{o} \rightarrow \pi^{+} + \pi^{-} \qquad 40\%,$$
$$\rightarrow \pi^{o} + \pi^{o} \qquad 10\%,$$
$$\rightarrow \pi^{+} + \mu^{-} + \bar{\nu} \qquad ?,$$
$$\rightarrow \pi^{-} + \mu^{+} + \nu \qquad ?,$$
$$K^{o} \rightarrow \pi^{+} + e^{-} + \bar{\nu} \qquad ?,$$
$$\rightarrow \pi^{-} + e^{+} + \nu \qquad ?,$$
$$\rightarrow \pi^{+} + \pi^{-} + \pi^{o} \qquad ?,$$

Sometimes, the p-p interaction yields $\bar{\Xi}$. $\bar{\Xi}$ decays into many types of particles. Examples of the decays and the life times are as follows:

Ξ^-	$\rightarrow \Lambda^0 + \pi^-$		10^{-9} sec.,
Λ^0	$\rightarrow p + \pi^-$	65%	2.7×10^{-10} sec.,
	$\rightarrow n + \pi^0$	35%	? ,
π^+	$\rightarrow \mu^+ + \nu$	100%	2.6×10^{-8} sec. ,
	$\rightarrow e^+ + \nu$	.01%	? ,
π^-	$\rightarrow \mu^- + \bar{\nu}$		2.6×10^{-8} sec. ,
π^0	$\rightarrow 2\gamma$	98.8%	10^{-5} sec. ,
	$\rightarrow \gamma + e^+ + e^-$	1.2%	? ,
	$\rightarrow 2e^+ + 2e^-$	0.004%	? ,
$\mu^\pm$	$\rightarrow e^\pm + \nu + \bar{\nu}$		2.2×10^{-6} sec. ,
n	$\rightarrow p + e^- + \bar{\nu}$		17.3 min..

From the equations of the decay it is seen that the final products of these particles are μ-mesons, protons and also electrons and photons. Consequently, these particles should be found at sea level. This result was supported by Bernadini, Cacciapuoti and Quezzoli(14).

Then it is concluded that the cosmic ray particles near sea level contain the following kinds of particles:

(a) charged particles, positive and negative electrons, positive and negative mesons and protons;

(b) nonionizing particles, neutrons, photons and neutrinos.

At sea level proton come from both primary and secondary cosmic rays, most of their momentum are less than 600 Mev./c, as found by Blackett(15). At the top of the atmosphere the momentum greater than 1000 Bev./c can be found.

A neutron will cause nuclear events if its energy is in kiloelectron volts range. If the energy decreases to about 1 electronvolt, it will be absorbed by N^{14} as shown,

$$N^{14} + n \rightarrow C^{14} + p .$$

However, most of the neutrons may not attain energies low enough to cause the reactions with nitrogen nuclei, since they decay into protons, and electron and antineutrinos with the mean life of 770 seconds as shown in the following equation,

$$n \rightarrow p + e^{-} + \bar{\nu}.$$

Mesons came from the interaction of the primary protons with the air. π-mesons can travel only about 30 metres, since they decay into μ-mesons and neutrinos with the mean life of 2.6×10^{-8} seconds as shown,

$$\pi^{\pm} \rightarrow \mu^{\pm} + \nu + \bar{\nu} .$$

A relativistic muon is much more penetrating than a relativistic proton since its cross section is very small ($10^{-27} cm^{2}$.) compared with the proton cross section.

For electrons and photons, we cannot distinguish between them when either has energy in the range of million electron-volts or higher due to the cascade theory. Sources of these components come from the disintegration of muons as shown,

$$\mu^{\pm} \rightarrow e^{\pm} + \bar{v} + v .$$

At a few hundreds gm/cm^2 depth of the atmosphere the intensity of this kind of particles is very large.

2.3 Energy Spectrum of Cosmic Rays.

The primary particles are mainly protons but electrons, α-particles and heavier nuclei whose atomic number, Z, as high as or up to 26 are also found.

The energy spectrum of the primary particle can be determined by the striking property in a wide variety of methods. For example, by its penetrating power. By using photographic plate or nuclear emulsion sent to the upper atmosphere, it is found that some protons have energy as high as 10^{18} ev. The approximate expression for the flux of total energies E of the incoming particles is given by (9)

$$N(E) = \frac{0.3}{E^{2.5\pm0.2}} \quad \text{for} \quad E > 10 \text{ Bev.}$$

where N(E) is the number of incoming protons per unit solid angle per sec. per cm^2. per Bev..

2.4 Components of Cosmic Rays.

There are two main kinds of components (16),

(a) nuclear interaction component,

(b) soft and hard component.

The hard and soft component can be separated by a thick layer of absorber. The thickness can be found by the absorption curve as shown by Street, Woodward and Stevenson's experiment (17). In the experiment the arrangement of the counters, absorbers is shown in Fig.2. When the triple coincidence count rate is plotted against thickness of absorber, the curve in Fig. 2b is obtained.

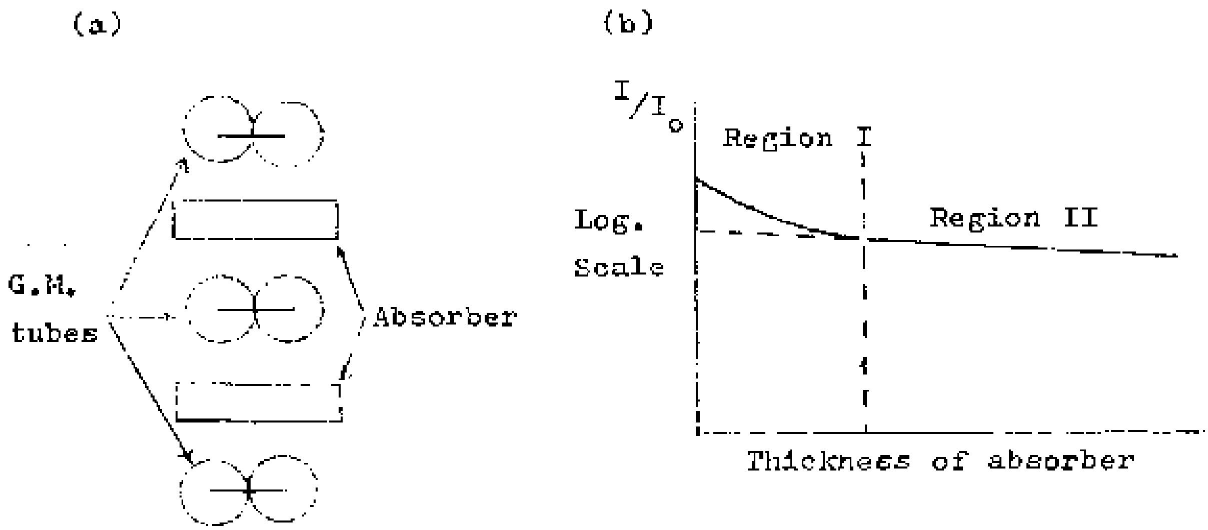


Fig. 2 Counter Arrangement and Absorption Curve.

From this curve it is seen that there are two regions. The curve region, at small absorber's thickness, is the absorption of both the soft and hard component. The straight region, which shows the absorption similar to that of γ-rays, is caused by only the hard component. Thus, the soft component may be separated by sufficient shielding.

2.5 Geomagnetic Effect.

When a charged particle move into a magnetic field, it will move in a helical path around the magnetic line of force.

Then the particle of cosmic rays should act like the particle in the magnetic field, when it reaches the earth's magnetosphere. In the year 1900 a Norwegian physicist Carl Störmer derived the formula for a charged particle in the earth's magnetic field. Lemaitre and Vallarta in 1933 improved and applied Störmer theory for cosmic rays.

Enrico Fermi's result (10) of the derivation of the equation of motion for charged particles in the earth's magnetic field is the same as that of Störmer, Lemaitre and Vallarta. For a particle arriving in the meridian plane, the momentum of the particle is given by

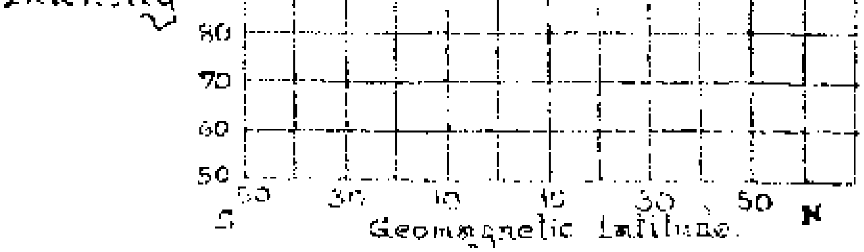
$$p > 15Z\cos^4\lambda \quad \text{Bev./c},$$

where p is the momentum of incoming particle,

Z is the total charge of the particle,

and λ is the geomagnetic latitude.

The above inequality shows that the particle which can reach the earth's surface should have the momentum greater than $15\cos^4\lambda$ Bev./c. It also shows that the intensity of cosmic rays depends on the geomagnetic latitude. The intensity at high latitude is greater than the intensity near the equator. The variation is shown in Fig.5



The Störmer theory was confirmed by W.H. Bennett (11). His experiment showed the forbidden and allowed regions. When the particles move into the earth's magnetic field with the proper angle, they will enter the earth's magnetic field and move along the lines of force, if they are at the wrong angle they will reflect back into space. For a very high energy particle, it can reach the earth without being deflected by the magnetic field. At the magnetic poles of the earth it is very easy for the particle to reach the earth's atmosphere. Since they cause ionization of the gases in the atmosphere, the gases emit visible light, This phenomenon is called the aurora. Sometimes radio wave and heat are also emitted.

2.6 Radiation Belts.

During the IGY the study of cosmic rays was made by many scientists, because at this time the sun activity was maximum. A number of rockets were launched at both poles of the earth and it was found that at high altitude the intensity is very large. The results from satellite and rockets are shown in Fig.4 and Fig.5.

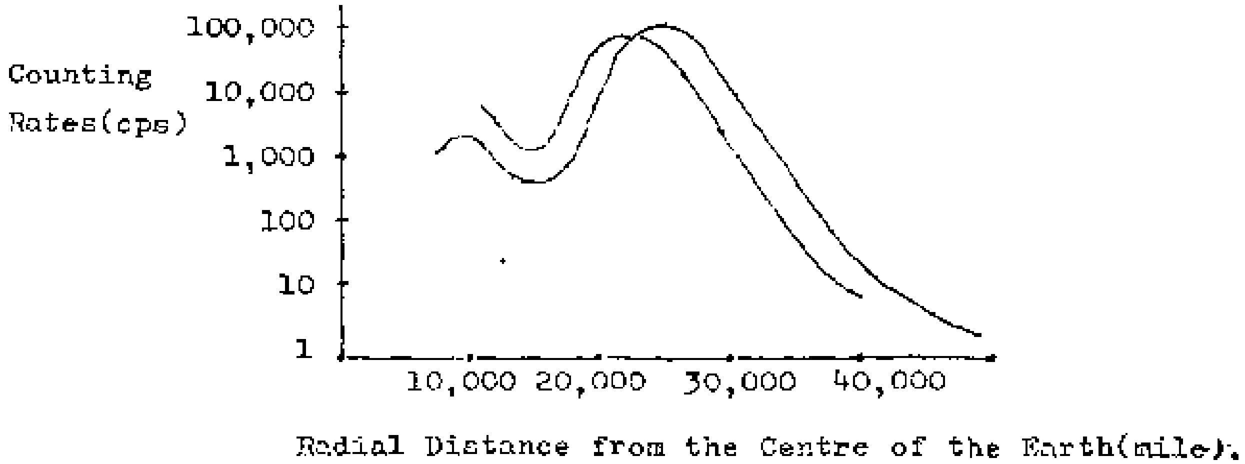


Fig. 4 Pioneer III data of the Count rates vs. Radial Distance(12).

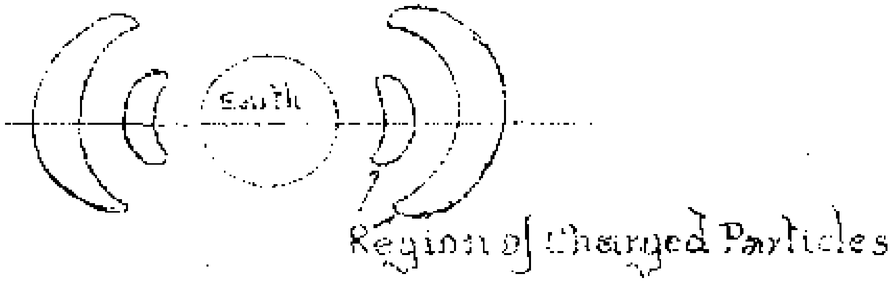


Fig.5 The Structure of the Radiation Belts.

The trapping of the particles can be explained by Störmer theory. It is believed that the particles in these belts largely come from the sun. The particles are injected into the earth's magnetic field, where they are reflected into the corkscrew trajectories around the magnetic lines of force and are trapped. Van Allen (12) suggested that the radiation belts resemble a sort of leaky bucket, constantly refilled from the sun and draining away into the atmosphere with the same rate. It is also believed that the origin of the outer belt is directly from the sun, while the inner belt particles are produced by neutron decays.

When the results of the rockets going up into the dark side of the earth (7) it was found that when there was a solar wind passing through the earth, the magnetosphere fluctuated. In the dark side the magnetosphere may extend to 100,000 miles, and in the day side it may be 25,000 miles. When the solar wind is small, the magnetosphere is about 40,000 miles from the earth. The shapes of the radiation belts vary with the solar wind is shown in Fig.6.

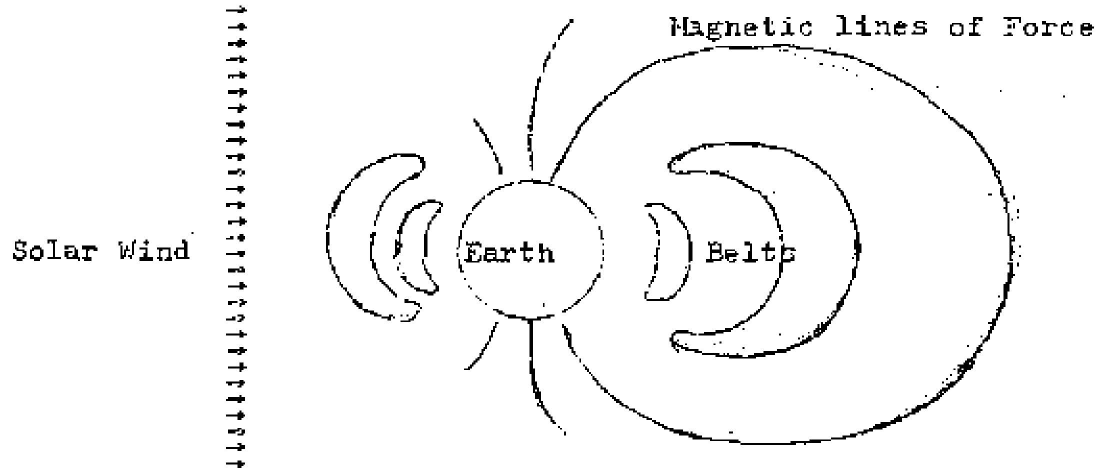


Fig.6 The Belts and Magnetosphere Change Caused by the Solar Wind(7).

The following are conclusions made by Van Allen(6).

a) The composition of the inner belt is quite different from that of the outer belt.

b) In the inner zone protons have energies of the order of 100 million electron volts, and the electrons in the order of 1 million electron volts.

c) Most of the particles in the outer zone are electrons; the upper limit of their energies is about 100 kiloelectron volts.

d) The inner zone is more stable than the outer zone.

e) The temporal fluctuations of the outer zone are apparently associated with solar activity.

f) The variation of the geographic effects, such as aurora, air glow, atmospheric heating and magnetic storms are associated with the outer zone.

g) The energy of incoming particles is about 10^4 electron volts in a cloud of solar gas and then the particles are accelerated to high energy by magneto-hydrodynamic waves or by other processes in the local environment of the earth.

h) The position of the particles in the zones is a function of energy. The electrons in the inner zone at the altitude of 750 miles have energies greater than 160 kiloelectron volts. The protons of energy 100 million electron volts at the outer zone move in circle around the line of force with diameter of 3,000 miles, proton of energy 100 kiloelectron volts moves with diameter 100 miles, and electrons of energy 100 kiloelectron volts move with diameter 1 mile.

2.7 The Variation of Cosmic Rays.

The intensity of cosmic rays at sea level varies with many factors, for example the temperature effect, barometer effect, diurnal variation, seasonal variation, and the sun's activity.

(a) Diurnal Variation.

This variation can be interpreted as the radiation of neutral particles, from decay and from interaction. Most of the charged particles from the sun are trapped in the belts. The rate of charged particles emitting from the belt is the same as the rate of trapping in the belt (12). Then the intensities of charged particles during the day and the night should be the same due to the equal rate of trapping and reemitting. But the factor that makes the difference is the neutral particles from the sun, as found by Bennett, Stearns and Compton (18)

(b) Seasonal Variation.

The seasonal variation of cosmic rays was detected in 1937 by Compton and Turner (19). From the works of Maeda and Patel (20) on the seasonal variation of cosmic ray intensity in polar regions, it was found that the variation is reversed between the northern and southern hemispheres.

(c) Temperature effect.

From Section 2.2 it can be seen that most of the intensity at sea level is from secondaries, which are formed near the surface of the atmosphere. From the meteorological data it is found that the upper surface of the atmosphere is not at constant height. It changes according to the temperature on the earth. At high temperature this level is higher, then mesons will decay before reaching the ground. Blackett (21) derived the value of the temperature coefficient for correcting the cosmic ray intensity. He found the average temperature coefficient α between the height 16 to 32 kilometres to be $-0.18 \pm 0.011\%/^{o}C$ at the standard temperature of $10^{o}C$.

(d) Barometer Effect.

This effect can be explained as the absorption of the atmosphere. At high pressure the intensity decreases according to the absorption. Duperier (22) suggested this coefficient

$$\beta = -3.45 \quad \%/\text{cm. of mercury.}$$

Janossy (23) derived this value

$$\beta = -3.5 \quad \%/\text{cm. of mercury.}$$

Forbush (24) determined β by experiments from the year 1937 to 1960 and found

$$\beta = -3.4 \quad \%/\text{cm. of mercury.}$$

All the values of the coefficients β are referred to the standard pressure of 76 cm. of mercury.

(e) The Intensity Variation due to the Sun's Activity.

During the solar flares, Firor (25), Maeda and Patel (26), and Maeda, Patel and Singer (27) found the increasing rate of the cosmic ray intensity and it is found that the neutron telescope is the best detector for this variation.

For the best results of the cosmic ray measurements, the above variations should be taking into account.