CHAPTER III

COSMIC RAY VARIATIONS

In a region of the earth magnetic field, a primary particle is deflected. If the energy of the primary particle is very high, the deflection will be so small that it may be neglected. The deflection depends on the direction of the primary particle and the position relative to the earth. For a particle moving in the magnetic equatorial plane, its trajectory is perpendicular to the magnetic field. By the rule of the magnetic deflection, it will be simply seen that this particle is deflected to the east, if it is positively charged. Consequently, the particle seems to come from the west. If it is, however, a low energy particle, it turns right and may make a complete turn. Depending on the latitude, the altitude, the direction, and its energy, a high energy particle may reach the earth at a place. At the equator a particle needs more energy than it needs at the pole to reach the earth.

Thus, it is seen that the earth magnetic field plays an important role in the trajectories of the cosmic rays. The factors causing the variations of cosmic rays in the various parts on the earth can be summarized into several effects.

1. Geomagnetic Effects.

The study of the motion of a charged particle in the earth magnetic field has been developed by Stormer in 1931 (9), and later in detail by Lemaitre and Vallarta (10). According to their theory the magnetic field of the earth may be considered as due to a magnetic dipole of moment $\mu = 8.1 \times 10^{25}$ ergs/gauss, located near the center of the earth and pointing roughly along the direction of the north south magnetic poles.

At the point whose distance is r away from the dipole, the magnetic field H decreases as r^{-3} according to the equation,

$$H = \frac{\mu \left(\cos \lambda \ \underline{e}_{\lambda} - 2 \sin \lambda \ \underline{e}_{r}\right)}{r^3} , \qquad (1)$$

where $\underline{e}_r$, $\underline{e}_{\lambda}$, $\underline{e}_{\phi}$ are the unit vectors pointing to the zenith, the north direction, and the west direction, respectively.

For the motion of a charged particle moving perpendicular to a uniform magnetic field at the equator we know that the force F acting on the particle is given by

$$F = \frac{H \, (Ze) \, v}{c} . \qquad (2)$$

For a stable orbit of radius ρ this force must be balanced by the centrifugal force

$$F = \frac{m v^2}{\rho} ; \qquad (3)$$

thus, we get

$$\frac{H\,(Ze)\,v}{c} = \frac{m\,v^2}{\rho} , \qquad (4)$$

and $\qquad P = pc/Ze = H\rho ,$

where P is the magnetic regidity,

ρ is the radius of curvature of the orbit,

p is the particle's momentum,

Ze is its charge,

c is the velocity of light.

A particle may be considered as relatively unaffected by the magnetic field H if the radius of curvature of its orbit is much larger than r_e, the radius of the earth. Thus we can find the minimum order of magnitude of P such that the particle is able to reach the earth from the condition :

$$P > H\,r_e = 0.31 \times 6.4 \times 10^8 = 2 \times 10^8 \text{ gauss cm..}$$

For $Z = 1$, this corresponds to an energy of about 60 Bev.. It is said to be in an allowed region. If the particle is more deflected, with the orbit less than r_e, it will return to outer space. Thus the region is called forbidden region.

According to the Stormer theroy (11) , the following equation can be derived :

$$R \cos\lambda \cos\gamma + \frac{\cos^2\lambda}{R} = B \quad \text{for a positive particle,} \qquad (5)$$

and $$\cos\gamma = \frac{B}{R\cos\lambda} - \frac{\cos\lambda}{R^2} , \quad -1 < \cos\gamma < 1, \qquad (6)$$

where λ is the geomagnetic latitude,

γ is the angle between the trajectory of cosmic ray particle and the vector pointing west,

R is the radius of curvature of the orbit in Störmer unit

1 Störmer unit is $\frac{\mu}{p}$, $\mu = 8.1 \times 10^{25}$ ergs/gauss,

B is impact parameter in Störmer unit.

For any given value of B, certain areas in this plane where $\cos\gamma > 1$ or $\cos\gamma < -1$, will be forbidden to the particle. Figure 4 illustrates these forbidden regions for a particle of positive charge. The same figure will apply for a negative particle if the sign of B is changed, and the cross hatchings are interchanged. The area where $-1 < \cos\gamma < 1$ will be allowed for the particle.

So long as $R_e > 1$ are chosen, it is not necessary to compute B, we know that our mark falls in an allowed region of type 1 area. This means that, so long as $R_e > 1$ ($E > 60$ Dev.), γ is arbitrary. The particles can come in from any direction it pleases.

If $R_c < 1$, however, we must calculate B before any dicision. If our choice of γ has been made as $B < 2$ (for positive particles) the jaws of the forbidden region will not be closed, (see figure 4). But if γ is too small such that $B > 2$, the jaws will be closed, corresponding to allowed region type II, the particle can not get to the earth. This type II allowed region does not allow the primary particles from space to reach. Only the particle accelerated by some source on the earth can come in.

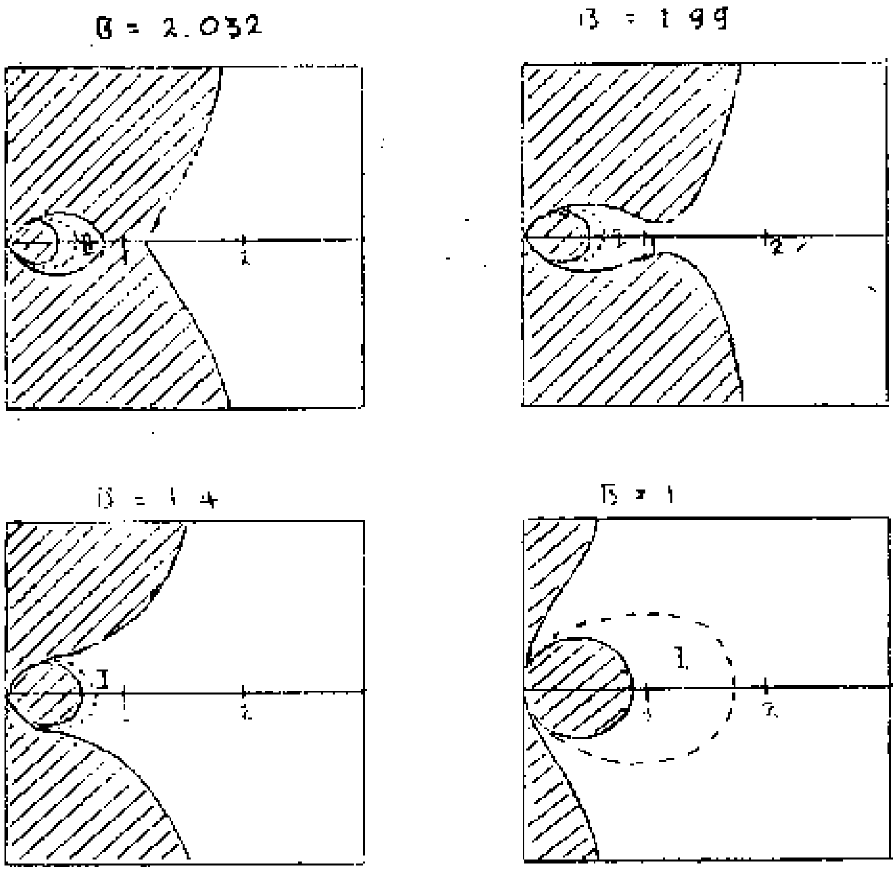

Fig. 4 : Forbidden Regions of the Meridian Plane for Several Values of B

An allowed region is the area which the incoming particles can reach. Consider the value of ξ for $Z > 0$, $B < 2$. from the Eq. (6) we will get

$$\cos\xi < \frac{2}{R_e \cos\lambda} - \frac{\cos\lambda}{R_e^2} ,$$

where R_e is the radius of curvature of the earth in Störmer unit.

Let γ_{0+} be the minimum angle that the direction of the velocity of the particle makes with a vector pointing west. $\cos\gamma$, therefore, is the maximum value. Thus the equation will be

$$\cos\gamma_{0+} = \frac{2}{R_e \cos\lambda} - \frac{\cos\lambda}{R_e^2} \qquad (7)$$

The allowed region looks like a cone as shown in Fig. 5. Thus it is called an allowed cone.

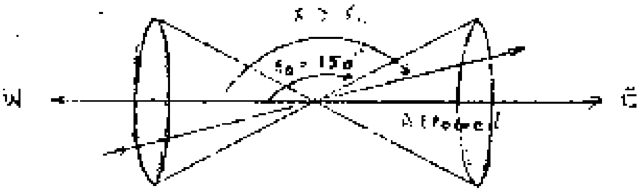

Fig. 5 : An Allowed Cone

For particles arriving in the meridian plane, $\cos\gamma = 0$, we can find the mimimum energy of the incoming particle to reach the earth as follows,

$$P > 15\ Z \cos^4\lambda \quad \text{Bev./c.} \qquad (8)$$

P is called the cut-off energy of the cosmic radiation.

2. Shadow Effect.

If a particle comes to the earth as shown in Fig. 6 , the trajectory cuts the surface of the earth at two points, at only one of which is the particle observable, for at the other, observation has been forbidden by the shadow of the earth. It

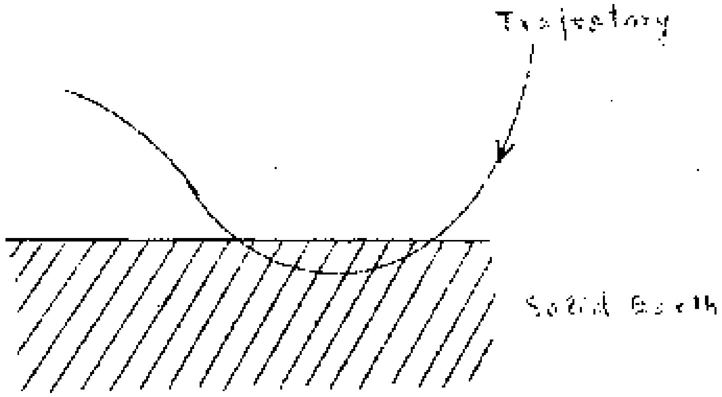

Fig. 6 : The Shadow Effect of the Earth

corresponds to observing a direction below the horizon. At the equator, no shadow effect occurs. The shadow effect increases as the geomagnetic latitude increases, and it is most prominent near the pole. This effect has been considered by Lemaitre and Vallarta in their more rigorous treatment. Therefore, in order to find all allowed directions, it is necessary to determine which parts of the cone lie in the earth's shadow. This effect provides the allowed cone asymmetry with respect to the north-south direction.

3. Latitude Effect.

From Eq.(8), we see that the critical momentum decreases as we move northward from the equator. So we should expect the intensity of the cosmic radiation to increase as the critical momentum decreases.

4. Longitude Effect.

An effect closely connected with the latitude effect is the longitude effect. The cosmic ray intensity along the equator is found to vary with geomagnetic longitude. Observations along the equator show that the intensity has a minimum in Peru, and a maximum near the Phillipines. The longitude effect was observed by Clay and his co-workers (12), and also by Millikan (13). It is due to the eccentric position of the eqivalent magnetic dipole inside the earth. According to measurements by Pickering, the longitude effect does not increase with increasing altitude.

5. Temperature Effect.

It was found that the vertical cosmic ray intensity varies with the atmospheric temperature. The intensity decreases as the temperature rises. This strange effect was interpreted by Blackett (14) in the following way. The mesons are formed near the top of the atmosphere. Because of the instability of mesons, only a certain fraction of these mesons reaches the sea level. If the temperature of the atmosphere rises, the air expands, and the layers where the mesons are formed shifted upwards; therefore, as the temperature rises, the mesons have to travel greater distances and hence more mesons decay before reaching the sea level. Thus the temperature effect is simply caused by the expansion of the atmosphere, and the consequent additional decay resulting from the expansion.

6. East-West Asymmetry.

The magnetic field of the earth affects not only the total intensity of cosmic rays, but also the directional distribution of radiations at any point of observation. If the primary particles are positively charged, coming from the outer space, they will be deflected to the east. We may therefore say that the forbidden cone for positively charged particles points towards the east. Thus the intensity from the west is greater than that from the east. This phenomenon is called the East-West asymmetry. It is usual to define the East-West effect as

$$\epsilon = \frac{I_W(\theta) - I_E(\theta)}{\frac{1}{2}\left[I_W(\theta) + I_E(\theta) \right]}$$

Where $I_W(\theta)$ and $I_E(\theta)$ are the intensities at zenith angle θ towards the west and east, respectively.

By the work of many investigators, first by Johnson (1), it is found that the cosmic ray intensity from the west exceeds the intensity from the east. So it may be concluded that the primary cosmic rays contain mostly positively charged particles. The effect can be observed at sea level, but at high altitude the effect increases gradually. The East-West asymmetry is maximum at the equator and decreases as the latitude increases.

If the primary particles come from inside the atmosphere, they can not be deflected by the earth's magnetic field, but they can reach the earth's surface both in allowed and forbidden regions.