The East-West Asymmetry of the Cosmic Radiation in High Latitudes and the Excess of Positive Mesotrons

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The slight east-west asymmetry of the cosmic radiation in high latitudes, now confirmed by Seidl, is interpreted to be the result of the deflection by the earth's magnetic field of the mesotron component while the rays are losing energy by ionization in the atmosphere. Since this component contains about twenty percent more positive than negative rays these deflections result in an asymmetry. Orbits of rays, including those in the range of energy where rest mass cannot be neglected, have been investigated and the deflections determined. It is assumed that deflections without energy loss, namely, those of the primary rays described by the theory of Lemaître and Vallarta, result in a symmetrical distribution for the energy ranges concerned. The asymmetry is traced to the *difference* between the actual deflection and that of a ray which loses no energy. The "difference" deflection δ shifts the angular distribution so that rays which, in the absence of a field, would have produced an intensity proportional to $\cos^2 \zeta$ at zenith angle ζ actually produce this intensity at an angle $\zeta+\delta$. Asymmetries calculated in this way agree with the observed values, and give the correct variation of asymmetry with zenith angle and elevation. Although the data are meager, the theory seems to be in accord with the existing evidence regarding the effect of absorbing material upon the asymmetry.

INTRODUCTION

It is now recognized that the east-west asymmetry of the cosmic radiation occurring in the equatorial zone is produced by the deflection of primary cosmic rays before their entry into the earth's atmosphere, and that it arises from an excess of positive particles in that part of the primary radiation responsible for the intensity in the lower part of the atmosphere. These primary deflections, however, do not explain the slight asymmetry observed in high latitudes nor the comparatively large asymmetries noted at zenith angles near the horizon within the equatorial belt. Since the slight increase of cosmic-ray intensity with latitude at latitudes above the so-called knee of the latitude effect has now been explained as a temperature effect,[1] it is probable that no rays in the field sensitive range of energy at these high latitudes make their effects felt at sea level. It has been shown by Lemaître and Vallarta that rays of energy greater than the field sensitive range, the only rays whose effects are felt at sea level in high latitudes, are incident uniformly from all directions, and the high latitude asymmetry cannot be traced to the deflections of the primary rays themselves. But as rays lose energy in the atmosphere, they are deflected by the magnetic field from their primary orbits. Since the observations of Hughes and others[2] have shown the presence in the atmosphere of about twenty percent more positive than negative mesotrons, these deflections produce an asymmetry in the angular distribution.

Deflections of this type have been discussed by Bowen[3] and by Rossi[4] who have shown that no appreciable part of the equatorial asymmetry can be explained in this way, but it appears from the present treatment that this effect can account for the high latitude asymmetry and for the asymmetries at large zenith angles in the equatorial belt. Since we now have a considerably greater knowledge of the behavior and the composition of the cosmic radiation than was available at the time of the former discussions of this effect, the present treatment is somewhat different from those of the above authors.

The first evidence of an east-west effect was observed by Johnson and Street[5] on the summit of Mount Washington, New Hampshire, geomagnetic latitude 56°, considerably above the knee of the latitude effect which recent investigations have placed at about the latitude of 40°.

[1] A. H. Compton and R. N. Turner, Phys. Rev. **52**, 799 (1937); P. M. S. Blackett, *ibid.* **54**, 973 (1938).

[2] D. J. Hughes, Phys. Rev. **57**, 592 (1940); P. M. S. Blackett, Proc. Roy. Soc. **A159**, 1 (1937); L. Leprince-Ringuet and J. Crussard, J. de phys. et rad. **8**, 207 (1937).

[3] I. S. Bowen, Phys. Rev. **45**, 349 (1934).

[4] B. Rossi, Rendi Lincei **15**, 62 (1932).

[5] T. H. Johnson, J. Frank. Inst. **214**, 665 (1932); T. H. Johnson and J. C. Street, Phys. Rev. **43**, 381 (1933).

Later and more accurate measurements in Pennsylvania and in Colorado by Johnson and Stevenson[6] and by Stearns and Froman[7] have confirmed the existence of a high latitude asymmetry and have shown that it amounts to about one percent at 30° from the zenith, probably increasing to about five percent at 60°. The effect is almost independent of elevation up to the summit of Mount Evans, 14,000 feet above sea level. In a recent extended series of observations carried out at Troy, New York, 54° N geomagnetic latitude, Seidl[8] has measured the asymmetry at an average zenith angle of 20° and has shown that it is not much affected by lead absorbing screens up to 25 cm thick, but probably diminishes slightly with increase of lead thickness. In the equatorial belt the writer[6] has noted an indication of an abnormally high asymmetry close to the horizon where the normal asymmetry should disappear because of atmospheric absorption.

In order to account for these effects, we assume that the rays reaching sea level are symmetrically distributed upon their arrival at the top of the atmosphere or at the point where they are produced as secondaries of such symmetrically distributed primary radiation, but as the rays are slowed down by atmospheric ionization their paths become more and more curved and when they have reached the observer they have experienced a slight deflection from their original direction or the direction they would have had in the absence of energy losses. Any unbalance in the numbers of positives and negatives results in an asymmetry, for if the average deflection is δ, the intensity at zenith angle $\zeta+\delta$ corresponds to that occurring at angle ζ in the symmetrical distribution. The deflection is toward the west for positive rays and towards the east for negatives. When treated in this way it becomes unnecessary to consider the details of atmospheric absorption or of the instability of the mesotron, for the influence of these phenomena upon the probability that a ray will arrive at sea level from the direction concerned is already taken into account in determining the normal symmetric distribution.

Theory of the Deflections

Since we are concerned with an explanation of the east-west asymmetry, we will consider rays whose orbits lie in the east-west vertical plane. In calculating the deflection suffered by a cosmic ray during its trip through the atmosphere, the approximation will be used that the rate of loss of energy by ionization is independent of the energy and is equal to αm_0c^2 per cm of air at a pressure of one atmosphere. This approximation is accurate within a few percent for mesotron energies greater than about ten million volts and is expressed by

$$d\epsilon/ds=\alpha p, \tag{1}$$

where p is the pressure in atmospheres, s is the orbital distance measured backwards along the orbit from the position of the observer, and ϵm_0c^2 is the energy of the ray, i.e., $\epsilon=(1-\beta^2)^{-\frac{1}{2}}-1$. The radius of curvature of the ray in the earth's field, whose horizontal component is H, is given by

$$\rho=R(\epsilon^2+2\epsilon)^{\frac{1}{2}}, \tag{2}$$

where R stands for the quantity m_0c^2/eH.

The variation of ρ with orbital distance is then given by

$$d\rho/ds=(d\rho/d\epsilon)(d\epsilon/ds)=\alpha Rp(\epsilon+1)(\epsilon^2+2\epsilon)^{-\frac{1}{2}} \tag{3}$$

or by making use of Eq. (2)

$$d\rho/ds=\alpha Rp(1+R^2/\rho^2)^{\frac{1}{2}}. \tag{4}$$

[6] T. H. Johnson, Phys. Rev. **48**, 287 (1935); T. H. Johnson and E. C. Stevenson, *ibid.* **44**, 125 (1933).
[7] D. K. Froman and J. C. Stearns, Phys. Rev. **46**, 535 (1934).
[8] F. G. P. Seidl, Phys. Rev. **59**, 7 (1941), preceding paper.

TABLE I. *The atmospheric deflection δ, expressed in radians, for mesotrons of various energies as a function of the zenith angle of the orbits and the elevation of the observer.*

FINAL ENERGY EV $\times 10^{-8}$	0	1	2	4	8	15	30	60
Sea level								
$\zeta=0°$	0.077	0.049	0.039	0.028	0.017	0.010	0.0041	0.0015
20°	0.079	0.050	0.040	0.030	0.018	0.0105	0.0047	0.0017
40°	0.083	0.054	0.045	0.033	0.022	0.014	0.0060	0.0024
60°	0.093	0.063	0.054	0.042	0.030	0.0195	0.010	0.0044
Alt. 4300 m								
$\zeta=20°$	0.11	0.064	0.049	0.032	0.019	0.0095	0.0036	0.0012
40°	0.12	0.073	0.057	0.040	0.023	0.012	0.0049	0.0017
60°	0.13	0.080	0.069	0.052	0.033	0.019	0.0086	0.0034

If h_0 is the extent of the homogeneous atmosphere, the pressure at any height x above sea level is given approximately by $p=\exp(-x/h_0)$. Since, as the calculation will show, the maximum deflection does not exceed a few degrees, x may be replaced by $x_0+s\cos\zeta$ where ζ is the zenith angle of the ray when it reaches the observer, and x_0 is the height above sea level of the observer. Then Eq. (4) may be written

$$d\rho/ds=\alpha R(1+R^2/\rho^2)^{\frac{1}{2}}\exp\left[(-x_0-s\cos\zeta)/h_0\right]. \tag{5}$$

The integral of (5) is

$$\rho=\left[(a-be^{-\gamma s})^2-R^2\right]^{\frac{1}{2}}, \tag{6}$$

where $a=[\rho_0^2+R^2]^{\frac{1}{2}}$, ρ_0 is the initial radius of curvature of the ray upon its entry into the atmosphere at a height considered to be great compared with h_0 but small compared with the radius of the earth, b is R times the energy, expressed in units of m_0c^2, of a ray just able to penetrate from the top of the atmosphere to the observer, i.e.,

$$b=\alpha Rh_0\sec\zeta\exp(-x_0/h_0)\quad\text{and}\quad\gamma=(\cos\zeta)/h_0.$$

Writing $z=be^{-\gamma s}/a$ and $k=R/a$, the deflection of a ray during its passage through the atmosphere is

$$\theta=\int_{s=0}^{s_1}ds/\rho=-(1/\gamma a)\int_{z=b/a}^{(b/a)\exp(-\gamma s_1)}\left[z^{-1}(z^2-2z+1-k^2)^{-\frac{1}{2}}\right]dz, \tag{7}$$

where s_1 is some distance, large compared with $h_0\sec\zeta$ but small compared with the radius of the earth. On integrating Eq. (7) and putting in the limits, the total deflection is

$$\begin{aligned}\theta=(1/\gamma a)(1-k^2)^{-\frac{1}{2}}\{&\log\left[\{[1-(b/a)e^{-\gamma s_1}]^2-k^2\}^{\frac{1}{2}}+(1-k^2)^{\frac{1}{2}}-(b/a)e^{-\gamma s_1}(1-k^2)^{-\frac{1}{2}}\right]\\&-\log\left[\{[1-(b/a)]^2-k^2\}^{\frac{1}{2}}+(1-k^2)^{\frac{1}{2}}-(b/a)(1-k^2)^{-\frac{1}{2}}\right]\}+(s_1/a)(1-k^2)^{-\frac{1}{2}}.\end{aligned} \tag{8}$$

The last term of Eq. (8) is the deflection

$$\theta_0=\int_{s=0}^{s_1}\frac{ds}{\rho_0},$$

which the ray would have experienced over the same path if no energy had been lost by atmospheric ionization, a deflection which we assume would have resulted in a symmetric distribution at sea level. The increased deflection resulting from atmospheric energy losses is then $(\theta-\theta_0)$ and in the limit $(s_1=\infty)$ this converges to

$$\delta=\underset{s_1=\infty}{\text{limit}}\,(\theta-\theta_0)=\frac{1}{\gamma a(1-k^2)^{\frac{1}{2}}}\log\frac{2}{1-\dfrac{b}{a(1-k^2)}+\left[\dfrac{(1-b/a)^2-k^2}{1-k^2}\right]^{\frac{1}{2}}}. \tag{9}$$

The deflections calculated from Eq. (9) for mesotrons reaching the observer from various zenith angles at sea level and at 4300 m elevation are shown as a function of the final energy in Table I. In making these calculations the following values of the constants have been used: $\alpha=2.5\times10^{-5}$, corresponding to a mass energy of the mesotron of 10^8 electron volts, and an ionization loss of 2500 volts per cm at normal atmospheric pressure; $H=0.18$ c.g.s. unit, the value of the horizontal component of the earth's field at Troy; $h_0=8.0\times10^5$ cm; $R=18.5\times10^5$ cm.

It is an interesting feature of this form of the theory that a ray is completely stopped before it has been deflected through a very large angle. For example, a ray with initial radius of curvature $\rho_0=(b^2+2bR)^{\frac{1}{2}}$, having just enough energy to reach sea level along the orbit inclined at angle ζ from the zenith, is deviated by only 4° 21′ at $\zeta=0°$.

Calculation of the Asymmetry

Since the deflection is a function of the final energy of the ray, the average deflection depends upon the energy distribution of the radiation at sea level. Studies of the magnetic bending of cosmic rays in the cloud chamber[9] have shown this distribution to be of the form

$$N(E)dE=(A/E^n)dE, \quad \text{with } n \text{ about } 3.$$

The average deflection is then

$$\bar{\delta}=(n-1)E_1^{n-1}\int_{E_1}^{\infty}[\delta(E)/E^n]dE, \tag{10}$$

where the limit E_1 of the integral corresponds to the stopping power of the instrument, or, if no absorber is used in the instrument, this limit is about 2×10^8 electron volts below which it has been found[9] that very few mesotrons are present in the atmosphere. In Seidl's apparatus two thicknesses of lead shields have been used, one 14.5 cm thick and the other 25 cm thick, whereas in the experiments of the writer and in one of Seidl's experiments no lead was used. Corresponding to these thicknesses the low energy limits are 2.2×10^8 electron volts and 3.5×10^8 electron volts, respectively. The values of $\bar{\delta}$ calculated from Eq. (10) are shown in Table II.

If the positive or the negative rays are considered alone, the first-order effect of these deflections is to shift the angular distribution through the angle $\bar{\delta}$. The intensity which in the absence of this phenomenon would have appeared at any zenith angle ζ will actually be found at the angle $\zeta+\bar{\delta}$. Since the length of the path through the atmosphere is not greatly altered by these deflections, it is not necessary to bring into consideration phenomena which affect the probability that a ray will reach sea level along a given orbit, for these phenomena are operative in determining the normal angular distribution of the radiation. To a close approximation this distribution is given by

$$j(\zeta)=j_0\cos^2\zeta. \tag{11}$$

Hence, the difference of the intensities on the two sides of the zenith at angle ζ is

$$j(\zeta+\bar{\delta})-j(\zeta-\bar{\delta})=2\bar{\delta}(dj/d\zeta)=4\bar{\delta}j(\zeta)\tan\zeta.$$

The asymmetry, then, of the purely positive or of the purely negative component is

$$\alpha=2(j_w-j_e)/(j_w+j_e)=4\bar{\delta}\tan\zeta.$$

If, on the other hand, a fraction f of the total radiation consists of positives unbalanced by negatives, the asymmetry will have the value

$$\alpha=4f\bar{\delta}\tan\zeta.$$

The observations of Hughes indicate that $f=0.20$, there being more positives than negatives. With this value of f the calculated values of the asym-

Table II. *Values of the average deflection $\bar{\delta}$ in radians.*

Low Energy Limit	Sea Level $\zeta=20°$	40°	60°	4300 Meters 20°	40°	60°
$E_1=2.2\times10^8$ ev	0.031	0.033	0.045	0.034	0.043	0.054
$E_1=3.5\times10^8$ ev	0.023	0.024	0.030	0.023	0.029	0.042

Table III. *Calculated values of the asymmetry at various zenith angles and altitudes for two lead thicknesses.*

Low Energy Limit	Sea Level $\zeta=20°$	40°	60°	4300 Meters 20°	40°	60°
$E_1=2.2\times10^8$ ev	0.0089	0.022	0.061	0.010	0.029	0.075
$E_1=3.5\times10^8$ ev	0.0065	0.015	0.043	0.007	0.020	0.058

[9] P. M. S. Blackett, Proc. Roy. Soc. **A159**, 1 (1937).

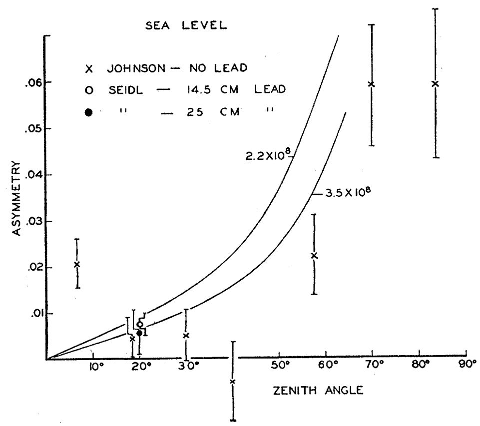

FIG. 1. The high latitude asymmetry at sea level, plotted against zenith angle. The curves show the theoretical values based upon an energy distribution proportional to E^{-3}, with lower limits at 2.2×10^8 electron volts and at 3.5×10^8 electron volts, corresponding respectively to lead absorber thicknesses of 14.5 cm and 25 cm. The points represent the experimental values obtained by Seidl and Johnson.

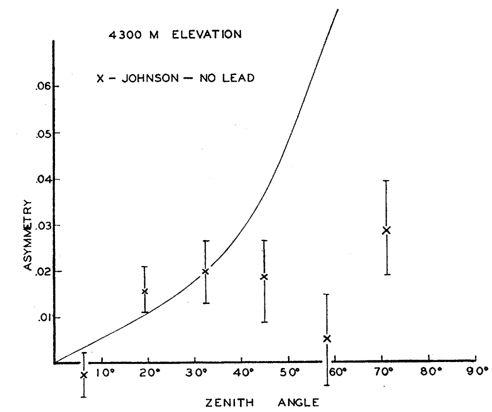

FIG. 2. The high latitude asymmetry at an elevation of 4300 meters above sea level (0.6 atmosphere). The curve shows the theoretical values based upon an E^{-3} distribution with a lower energy limit at 2.2×10^8 electron volts.

metry for the two lead thicknesses are given in Table III. Figures 1 and 2 show the variations of the asymmetry with zenith angle at the two elevations. The curves represent the calculated values, while the points indicate the values found by Seidl and the writer. In every case the probable errors are large, but there seems to be some justification for the belief that the theory gives an adequate representation of the data, both as regards the magnitude of the asymmetry and its variations with zenith angle and thickness of lead absorber. The theory gives a somewhat larger asymmetry than is observed near the horizon, especially at the higher elevation. This may indicate that the predominance of the positive component is not as pronounced at the higher elevations as that corresponding to the value $f=0.20$. This could be explained by the presence at the higher elevations of a larger fraction of soft component rays consisting of equal numbers of positive and negative electrons. It may also be noted that Blackett[10] in a more recent paper points out that the spectrum is nearly constant for energies less than 10^9 volts and at higher energies it falls off as E^{-2} or a little faster. An energy distribution of this type would give a higher average energy than that of the E^{-3} distribution upon which the calculations have been based, and a consequent lower asymmetry. Thus it seems possible to bring the theory into better accord with the asymmetry at zenith angles close to the horizon without disturbing its agreement with the data at higher angles at sea level. At the higher elevation, however, it would be necessary to invoke some asymmetry of the primary rays to explain the apparent peak at 30°. Such an assumption would not necessarily be out of harmony with other facts for the knee of the latitude effect may well lie above 51° at that elevation.

In conclusion, the writer takes pleasure in acknowledging several stimulating discussions of this problem with Mr. F. G. P. Seidl who has contributed essential elements in its final formulation.

[10] P. M. S. Blackett, Proc. Roy. Soc. **A165**, 11 (1938).