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The Path of a Secondary Cosmic-Ray Charged Particle in the Earth's Magnetic Field

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An analysis is made of the paths of secondary high energy charged particles ejected from the earth's atmosphere by primary cosmic-ray photons. This leads to the following conclusions. (1) As has generally been assumed the decrease in ionization in equatorial regions is much larger than can be explained by the deflection by the earth's magnetic field of the secondaries formed in the earth's atmosphere. (2) The observed east-west dissymmetry of Geiger tube counts can be explained by the deflection of secondaries formed in the earth's atmosphere provided an appropriate value of Q, the excess of positives over negatives, may be assumed. The small amount of the observed dissymmetry at high latitudes however sets so low an upper limit on Q that this mechanism appears to be inadequate to explain all of the observed dissymmetry at low latitudes.

RECENT cosmic-ray measurements by many observers have brought to light two latitude effects.[1] These are the decrease in ionization in an electroscope near the magnetic equator and the appearance of an east-west dissymmetry in Geiger tube counts in the same region. It is generally recognized that these effects are produced by the action of the earth's magnetic field in deflecting the high energy charged particles which are the immediate cause of the cosmic-ray ionization.

The present paper is a theoretical attempt to determine whether these experimental results may be quantitively explained by the action of the earth's field on secondary electrons (positive or negative) ejected by primary photons in the earth's atmosphere or whether it is necessary to postulate primary charged particles coming from outside the earth's atmosphere.

When an electron which has fallen through a potential of V volts passes normally through a magnetic field H the radius of curvature of its path r in cm is given by[1]

$$V=510{,}000[\{1+(0.00059\,Hr)^2\}^{\frac{1}{2}}-1]. \quad (1)$$

With cosmic-ray particles V is very large, usually of the order of several hundreds of millions of volts. Indeed if the energy of the particle is less than a million volts it is unable to penetrate most measuring instruments. Consequently the expression for r may be simplified to

$$r=V/300\,H. \quad (2)$$

Furthermore by direct counts it is found that a high energy particle dissipates its energy approximately uniformly along its path by the production of about 32 P ions per cm of its path in air at a pressure of P atmospheres. Since this requires about 1000 P electron-volts per cm the range (R) of such a particle is $V/1000\,P$. Since r and R are both proportional to V it follows at once that the radius of curvature (r) at any point on the path is proportional to the length of path (R) remaining before the particle is brought to rest. If the origin is placed at the end of the path this condition is satisfied by the equiangular spiral of the form

$$\rho=e^{r\theta/R}. \quad (3)$$

[1] Bull. Nat. Research Council 10, p. 85 (1925).

TABLE I. *Comparison of observed and calculated east-west dissymmetry.*

Location	Fractional excess west over east E	Observed angular shift φ	Pressure P	Horizontal component H	Calculated shift $\psi=3H/10P$	Excess of positives Q
Swarthmore[2]	0.028±0.006	0.43±0.09	0.98	0.18	3.2	0.13±0.03
Colorado[3]	.022± .005	.34± .08	.71	.22	5.3	.06± .02
Flagstaff[4]	.020± .018	.31± .28	.67	.26	6.7	.05± .04
Mexico City[5]	.084± .013	1.29± .20	.76	.31	7.0	.18± .03
" "[6]	.082± .006	1.26± .09				.18± .01
Peru[7]	.086	1.3	.97	.30	5.3	.25
	.112	1.7	.66	.30	7.8	.22
	.123	1.9	.58	.30	8.9	.21

I. Mean Deviation of Particles

Since in an equiangular spiral the radius vector maintains a constant angle with the tangent to the path, the change in direction of the path in passing from one point to another equals the difference in position angles of the two points.

$$\theta_0-\theta=(R\log\rho_0/\rho)/r=(R\log R_0/R)/r. \quad (4)$$

As in direction measurements with Geiger counters there is an equal probability of observing the particle at any point in its path the observed dissymmetry in the east-west counts will correspond to the average deviation ψ.

$$\psi=\frac{\int_0^{R_0}(R/r)\log(R_0/R)dR}{\int_0^{R_0}dR}=\frac{R}{r}=\frac{3H}{10P}. \quad (5)$$

Both theoretical and experimental evidence indicates that these very high energy particles occasionally suffer very large losses by ejecting other charged particles with high energy thus cutting down the range of the original particle to a small fraction of the above value of R. However, it can easily be shown that the mean deviation averaged over the paths of the original particle and of all particles ejected by it, is exactly that given in (5) for the single particle. In all of these derivations it is necessary to assume that the initial energy of all particles is large compared to that required to pass through the walls of the counters. Otherwise the counters cannot be considered as giving all parts of the paths equal weights, a condition which was assumed in taking the above averages.

ψ as given by Eq. (5) represents the mean deviation of a single particle or of any group of particles provided they are all of the same sign. If particles of both signs are present ψ must be multiplied by a factor Q which is equal to the excess in the number of one sign over that of the other divided by the total number of particles.

The east-west dissymmetry in Geiger counts has been measured at the locations given in the first column of Table I. In the second column an attempt has been made to place the readings of all observers on a common basis by listing the value of the quantity E which is the average, for all angles between 30° and 50° inclusive, of the ratio of the difference between west and east to the mean of west and east. A study of the complete curve of count frequency as a function of altitude angle for the cases where it has been determined, indicates that a shift in the center of symmetry of the curve of φ degrees from the vertical corresponds to a value of E of about 0.065φ. Assuming this relationship holds for all localities we obtain the values of φ in the third column. The sixth column gives the value of ψ (in degrees), i.e., the mean deviation of a secondary electron, corresponding to the values of P and H given in the fourth and fifth columns. The last column lists the value of $Q=(\varphi/\psi)$, i.e., the excess of positives, necessary to explain the observed dissymmetry if this is caused solely by the deflection of secondaries.

From the table it is at once evident that the deflection of secondaries is adequate to account for the observed dissymmetry provided we can

[2] T. H. Johnson and E. C. Stevenson, Phys. Rev. **44**, 125 (1933).
[3] E. C. Stevenson, Phys. Rev. **44**, 855 (1933).
[4] S. A. Korff, Phys. Rev. **44**, 515 (1933).
[5] L. Alvarez and A. H. Compton, Phys. Rev. **43**, 835 (1933).
[6] T. H. Johnson, Phys. Rev. **43**, 834 (1933).
[7] T. H. Johnson, Phys. Rev. **44**, 856 (1933).

assume an appropriate value for the excess of positives over negatives at each latitude.

Anderson's direct counts of positive and negative tracks in a Wilson expansion chamber give $Q=0.0\pm0.04$. Since however most of these secondary particles are ejected from the metal parts of the surrounding magnet it is not certain that this value of Q can be applied to the Geiger counter experiments in which the secondary particles are ejected from air.

If these secondary electrons are ejected by primary photons Q should have the same value at all latitudes since the earth's field has no effect on the intensity or quality of the incoming photons. Furthermore even though we assume that all of the dissymmetry at Flagstaff or in Colorado is caused by the deflection of secondaries the largest value of Q that we can justify is not much more than 0.06. This value of Q is, however, too small to explain all of the dissymmetry near the equator.

Dr. Korff of this Institute is now making experiments in Peru to determine just what fraction of the observed dissymmetry may be assigned to the deflection of secondaries. In these experiments the east-west dissymmetry, when the secondaries come from a 30 cm lead block placed directly above the counters, is compared with the dissymmetry when there is an equivalent amount of air above them. Since R, the range of the secondaries, in the lead is negligible, the part of the dissymmetry produced by the deflection of secondary electrons is largely eliminated in the first arrangement.

II. Decrease in Ionization Near the Equator[8]

If an electron is ejected vertically downward and if it ionizes uniformly along its range (R) then the average vertical distance between the ions formed and the point of ejection is $R/2$ if the path is straight. If the path is the equiangular spiral discussed above a simple calculation shows that the average vertical component of the distance between ions and the point of ejection is reduced to $R/2(1+R^2/4r^2)$. Therefore, on the average, the secondary particles passing through an ionization chamber are ejected at a point $(R/2)(1-1/[1+R^2/4r^2])$ lower than when the magnetic field is not present. Consequently if the intensity of the primary photons is given by $I_0e^{-\beta x}$ the intensity of ionization will be decreased in the ratio

$$e^{-(\beta R/2)(1-1/[1+R^2/4r^2])}.$$

This reduces to $1-\beta R/8(r^2/R^2)$ approximately. If we make the usual assumption that the range of the secondary electron is small compared to that of the primary photon and insert the value of r/R deduced above this ratio differs from unity by at most a few tenths of a percent. As has generally been assumed, this mechanism is therefore entirely inadequate to explain the observed effect of about ten percent at sea level and about thirty or forty percent at the highest elevations investigated.

[8] This section merely confirms the conclusions reached by R. M. Langer by a different method. Phys. Rev. **43**, 215 (1933).