Bloembergen.[9] This effect will be even larger for other metals and will complicate the procedure for producing large amounts of polarization.

A more favorable feature of the electron resonance shift is that it should provide, in principle, a direct measurement of the degree of polarization obtained. For example, if one were to apply the microwave power, the resonance line would be shifted towards higher frequencies, or for fixed frequency, towards lower magnetic fields. The field would then have to be decreased gradually to a critical value at which maximum polarization is reached. Beyond this value the resonance would be lost suddenly, and the line would snap back to its original, low microwave power position. The polarization $\mathcal{P}$ is related to the critical shift by Eq. (18) and could be maintained by operating on the high field side of the resonance. For nuclei having a negative gyromagnetic ratio this shift would be in the opposite direction, since these nuclei will at first be depolarized and then lined up in the opposite direction by the action of the relaxation processes.

V. CONCLUSION

Within the framework of the single particle model an enhanced nuclear polarization is predicted as the result

of relaxation processes that occur when the electron-spin resonance is saturated. The possibility of producing large amounts of polarization by this technique is of great experimental interest, although the problems that would have to be solved are by no means trivial. Microwaves in the 1-cm range are appropriate, and considerable power may be needed, depending upon the value of the electronic relaxation time at liquid helium temperature. In order to avoid eddy current losses as well as excessive breadth of the electron resonance,[2] it would be necessary to use finely divided metallic samples of particle size somewhat smaller than a micron. The use of chemically impure samples to increase the electrical resistivity at low temperatures would be helpful in this regard.

In nuclear resonance experiments the signal strength is proportional to the degree of nuclear polarization, which is ordinarily quite small. Such nuclear resonances would be enhanced by several orders of magnitude if the electron resonance were saturated simultaneously. This interdependence could be used as a means for detecting the electron resonance. Other effects would be a disappearance of the nuclear resonance shift at high saturation and a decrease in the dipolar broadening of the nuclear line for large polarizations.

[9] W. Kohn and N. Bloembergen, Phys. Rev. 82, 263 (1951).

Effects of the Geomagnetic Field on Solar Cosmic Rays

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(Received June 2, 1953)

The force acting on a charged solar cosmic ray due to the action of the geomagnetic field has been analyzed in terms of its components along the E–W, the N–S, and the vertical directions. With certain simplifying assumptions, the relative magnitudes of these components and their directions have been determined for specific values of the geographic latitude λ of the place of observation as well as the declination δ and the hour angle t of the sun. The deflection that can be produced in the trajectories of solar cosmic rays is qualitatively discussed in terms of the resulting changes which may be expected in the hour of maximum of the diurnal variation of cosmic rays assumed to be due to particles from the sun. It appears that the hour of maximum should become later with increase of latitude. In a northern latitude, a north-pointing cosmic-ray telescope should reveal a diurnal variation with an earlier maximum than a south-pointing telescope. There is a possibility therefore of being able to interpret the experimental results of directional studies of the diurnal variation of cosmic rays in terms of geomagnetic effects.

INTRODUCTION

EVIDENCE[1-5] has been accumulating recently indicating that the sun continuously emits cosmic rays. These rays are believed to be responsible for a daily variation in the pressure-corrected meson intensity

measured in the lower atmosphere. The variation has a predominant 24 hourly harmonic component whose amplitude may be designated by M^D. The hour of maximum of the diurnal component can be expressed in terms of the angle $M\phi^D$ made by the radius vector of M^D with respect to midnight on a 24 hourly harmonic dial representation. In general, $M\phi^D$ is different from π as the maximum does not coincide with the local noon of the place of observation. This is believed to be due to the effect of the geomagnetic field on charged solar cosmic rays.

[1] Simpson, Fonger, and Wilcox, Phys. Rev. 85, 366 (1952).
[2] H. V. Neher and S. E. Forbush, Phys. Rev. 87, 889 (1952).
[3] Sarabhai, Desai, and Kane, Nature 171, 122 (1953).
[4] Sarabhai, Desai, and Kane, Proc. Indian Acad. Sci. A37, 287 (1953).
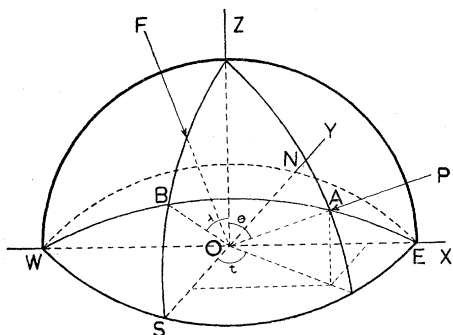[5] V. Sarabhai and R. P. Kane, Phys. Rev. 90, 204 (1953).

FIG. 1. Diagram showing the orientation of the initial momentum P of a solar cosmic ray and of the geomagnetic force F with respect to the E–W and N–S directions at a place in the northern hemisphere.

Considerable attention has been devoted in the past towards a theoretical understanding of the geomagnetic effects of cosmic rays. The main experimental facts that were sought to be explained concern the change of cosmic-ray intensity with latitude, longitude, zenith angle, and azimuth. The Lemaitre-Vallarta[6] theory, based on the equations of motion set out by Störmer in connection with the aurora borealis, has given a satisfactory explanation of the experimental observations. This theory, which uses Liouville's theorem, postulates an isotropic distribution of cosmic-ray primaries at great distances from the magnetic dipole. We cannot thus apply it for explaining the effects produced by the geomagnetic field on nonisotropic rays such as those coming from the sun.

Through extensive and laborious calculations involving numerical integration of the differential equations of motion, several workers, notably Störmer[7] and Lemaitre and Vallarta, have traced the orbits of charged particles directed from infinity towards a magnetic dipole. Brüche[8] and Malmfors[9] have studied

TABLE I. Components of P and F which produce deflection of the trajectory of a positively charged solar cosmic ray in the northern hemisphere when the sun is in the southern sky.

	Component of P	Component of F	Component of R	Deflection
1	P_{-z}	F_{+y}	R_{+x}	Eastwards
2	P_{+y}	F_{-z}	R_{-x}	Westwards
3	(a) Before noon P_{-x}	F_{-z}	R_{-y}	Southwards
	(b) Afternoon P_{+x}	F_{-z}	R_{+y}	Northwards
4	(a) Before noon P_{-x}	F_{+y}	R_{-z}	Downwards
	(b) Afternoon P_{+z}	F_{+y}	R_{+z}	Upwards

[6] G. Lemaitre and M. S. Vallarta, Phys. Rev. 43, 87 (1933).
[7] C. Störmer, Astrophys. Norvegica 2, No. 1 (1936).
[8] E. Brüche, Terr. Mag. Atmos. Elec. 36, 41 (1931).
[9] K. G. Malmfors, Arkiv. Mat. Astron. Fysik 32A, No. 8 (1945).

the same in laboratory experiments, and Malmfors has discussed the implications of these results on the diurnal variation of intensity. However, no study appears to have been made specifically on the geomagnetic effects of solar cosmic rays, nor on the changes that could take place by such effects in the diurnal variation assumed to be caused by solar cosmic rays.

If we wish to study the effect of the earth's magnetic field on $M\phi^D$, we are not as much interested in estimating the minimum momentum of allowed particles, as in the direction and magnitude of the deflections of the trajectories of solar cosmic rays that reach the earth at any point. It is possible by elementary considerations to examine the force that deflects the trajectories of solar particles in different latitudes at different hours and seasons. We show in this communication how such an analysis enables us to understand qualitatively, in terms of solar cosmic rays, some features of the meson diurnal variation which have hitherto proved difficult to interpret.

TABLE II. Values of (R_x/Pk) for specific values of λ, δ and $\pm t$.

λ	δ=0 ±π/2	±π/4	0	δ=−23.5° ±π/2	±π/4	0	δ=+23.5° ±π/2	±π/4	0
80	0	−1.35	−1.88				0.07	−1.11	−1.53
60	0	−0.98	−1.28			−1.67	0.17	−0.57	−0.63
40	0	−0.35	−0.23		−0.69	0.79	0.20	0.01	0.38
20	0	0.27	0.67		0.02	0.22	0.13	0.38	0.98
00	0	0.71	1.00	0	0.65	0.92	0	0.65	0.92
−20	0	0.27	0.67	0.13	0.38	0.98		0.02	0.22
−40	0	−0.35	−0.23	0.20	−0.01	0.38		−0.69	−0.79
−60	0	−0.98	−1.28	0.17	−0.57	−0.63			−1.67
−80	0	−1.35	−1.88	0.07	−1.11	−1.53			

FORCE DUE TO THE ACTION OF THE GEOMAGNETIC FIELD

For an elementary treatment, we only consider trajectories of solar cosmic rays of large enough "stiffness" so that after interaction with the field and on arrival on the surface of the earth, the initial components of the velocity of the particles in the vertical, the N–S and the E–W directions do not suffer a reversal of sign. We thereby exclude from consideration all cosmic rays of low momenta which are considerably deflected by the geomagnetic field. We also restrict ourselves to daylight hours when the sun is above the horizon. For the sake of simplification, we neglect the eccentricity of the geomagnetic dipole and the inclination of its axis with respect to the axis of rotation of the earth.

For any point 0 at geographic latitude λ, we can set up coordinate axes so that $+X$ points to the east, $+Y$ points to the north and $+Z$ points vertically upwards to the zenith. If 0 lies in the northern hemisphere at a latitude of about 50°N, Fig. 1 shows the orientation of the geomagnetic field F and the momentum P of a solar cosmic ray at equinox, before interaction with the field. The field F lies wholly in the meridian plane through 0 and has the component F_{-z} (or V) vertically downwards in the direction $-Z$, and F_{+y} (or H) pointing north. With the rotation of the

earth from west to east, the sun appears to move along the arc $EABW$ in the southern sky, crossing the meridian plane at B at noon. At all times of the day, the momentum of the particle has the components P_{+y} towards north and P_{-z} vertically downwards. Along the X axis, it has a component P_{-x} towards west before noon, and P_{+x} towards east in the afternoon. If, as a result of the geomagnetic field, a force R acts on the particle, one can consider its components along the coordinate axes in terms of the appropriate components of F and P.

Table I summarizes, for a positively charged solar cosmic ray, the components of force R that produce deflections of the trajectory in the east or west direction, the north or south direction and the vertically upward or downward direction. Since F has no component along the X axis, the components of P have effective interactions only with F_{+y} and F_{-z}. The indicated directions for the deflections are applicable to the northern hemisphere when the sun is in the southern half of the sky.

TABLE III. Values of (R_y/Pk) for specific values of λ, δ and $+t$ (in the afternoon). For the forenoon when t is negative, all signs in the table get reversed.

	$\delta=0$			$\delta=-23.5°$			$\delta=+23.5°$		
λ	$\pi/2$	$\pi/4$	0	$\pi/2$	$\pi/4$	0	$\pi/2$	$\pi/4$	0
80	1.96	1.37	0				1.80	1.20	0
60	1.74	1.15	0			0	1.63	0.91	0
40	1.28	0.76	0		0.88	0	1.24	0.59	0
20	0.68	0.35	0		0.42	0	0.67	0.32	0
00	0	0	0	0	0	0	0	0	0
−20	−0.68	−0.35	0	−0.67	−0.32	0		−0.42	0
−40	−1.28	−0.76	0	−1.24	−0.59	0		−0.88	0
−60	−1.74	−1.15	0	−1.63	−0.91	0			0
−80	−1.96	−1.37	0	−1.80	−1.20	0			

It will be noticed that along the E–W axis, there are in general two component forces R_{+x} and R_{-x} of opposite sign, which act simultaneously on the particle. Along the N–S axis or the vertical axis only one component operates at any moment; but along these axes the forces get reversed in direction as the sun crosses the meridian plane at noon.

EVALUATION OF COMPONENTS OF THE FORCE

The components of the geomagnetic field F are given by

$$F_x=0, \quad F_y=k\cos\lambda \quad \text{and} \quad F_z=2k\sin\lambda, \tag{1}$$

where $k=(M/r^3)$. M is the magnetic moment of the earth and r is the distance of the point 0 from the center of the earth. F_z is directed downwards in the northern hemisphere but upwards in the southern hemisphere.

The angular zenith distance θ of the sun is given by

$$\cos\theta=\cos\delta\,\cos\lambda\,\cos t+\sin\delta\,\sin\lambda, \tag{2}$$

where δ is the declination of the sun and t is the hour angle of the sun measured from noon. δ takes the

TABLE IV. Values of (R_z/Pk) for specific values of λ, δ and $+t$ (in the afternoon). For the forenoon when t is negative, all signs in the table get reversed.

	$\delta=0$			$\delta=-23.5°$			$\delta=+23.5°$		
λ	$\pi/2$	$\pi/4$	0	$\pi/2$	$\pi/4$	0	$\pi/2$	$\pi/4$	0
80	0.17	0.12	0				0.16	0.10	0
60	0.50	0.33	0			0	0.47	0.26	0
40	0.77	0.46	0		0.53	0	0.74	0.36	0
20	0.94	0.50	0		0.58	0	0.93	0.44	0
00	1.00	0.50	0	1.00	0.54	0	1.00	0.54	0
−20	0.94	0.50	0	0.93	0.44	0		0.58	0
−40	0.77	0.46	0	0.74	0.36	0		0.53	0
−60	0.50	0.33	0	0.47	0.26	0			0
−80	0.17	0.12	0	0.16	0.10	0			

values 0, $+23.5°$, and $-23.5°$ at the equinoxes, the summer solstice, and the winter solstice, respectively.

The three components of the momentum P of the particle are

$$P_x=P\sin t\,\sin\theta,$$
$$P_y=P\cos t\,\sin\theta, \tag{3}$$
$$P_z=P\cos\theta.$$

Hence, for any momentum P, the components of the deflecting force R due to geomagnetic interaction are

$$R_x=P_zF_y-P_yF_z,$$
$$R_y=P_xF_z, \tag{4}$$
$$R_z=P_xF_y.$$

These equations can be used for evaluating the values of R_x, R_y, and R_z for different values of λ, δ, and t.

Tables II, III, and IV indicate relative values of the components of force R along the X, Y, and Z axes respectively for different latitudes, at equinoxes and at the solstices, at 0600, 0900, 1200, 1500, and 1800 hours local time.

It is seen from Table II that at noon R_x has a maximum positive value at the latitude where the sun is directly overhead. With change of latitude either towards the north or the south, R_x first decreases, then reverses in sign and becomes increasingly negative as the polar regions are approached. At equinoxes, the reversal of the sign of R_x takes place at $\lambda=37°$ in both hemispheres. Expressed differently, it can be stated that solar cosmic rays have a force acting on them in the E–W direction which is such that in low latitudes the particles are deflected towards east and in higher latitudes towards west.

Changes in R_y, the force along the N–S direction, are seen from Table III. In the northern hemisphere, during daylight hours before noon, R_y is negative and the particles are deflected towards south. In the afternoon, R_y is positive and the particles are deflected towards north. In the southern hemisphere, the sign of R_y gets altered and in consequence, during morning hours, the particles get deflected towards north, and during the afternoon towards south. In both hemispheres, the magnitude of R_y increases with latitude.

TABLE V. Values of (R/Pk) for specific values of λ, δ, $\pm t$.

λ \ t	$\delta=0$			$\delta=-23.5°$			$\delta=+23.5°$		
	$\pm\pi/2$	$\pm\pi/4$	0	$\pm\pi/2$	$\pm\pi/4$	0	$\pm\pi/2$	$\pm\pi/4$	0
80	1.97	1.93	1.88				1.81	1.64	1.53
60	1.81	1.55	1.28			1.67	1.71	1.10	0.63
40	1.49	0.95	0.23		1.24	0.79	1.46	0.69	0.38
20	1.16	0.67	0.67		0.72	0.22	1.15	0.66	0.98
00	1.00	0.87	1.00	1.00	0.84	0.92	1.00	0.84	0.92
−20	1.16	0.67	0.67	1.15	0.66	0.98		0.72	0.22
−40	1.49	0.95	0.23	1.46	0.69	0.38		1.24	0.79
−60	1.81	1.55	1.28	1.71	1.10	0.63			1.67
−80	1.97	1.93	1.88	1.81	1.64	1.53			

The value of the force R_z in the vertical direction is shown in Table IV. At all places, during the hours before noon, R_z is negative and there is a downward deflection of the particles. In the afternoon there is an upward deflection. The force is most pronounced in low latitudes and becomes progressively weaker with increase of latitude.

The magnitude of the total force R acting on a solar cosmic ray is shown in Table V. During the hours near noon, R has a minimum value at an intermediate latitude between 20° and 50°, depending on the season. It has a maximum value in polar latitudes.

THE HOUR OF MAXIMUM OF THE DIURNAL VARIATION

It has been stated earlier that if solar cosmic rays are responsible for the diurnal variation of meson intensity, the displacement of the hour of maximum $M\phi^D$ from noon is an indication of geomagnetic effects on the charged particles of the primary radiation. Effects which deflect the trajectories towards east would result in a maximum earlier than noon. Hence $M\phi^D$ would be less than π. For a deflection towards west, $M\phi^D$ would be greater than π on account of the maximum occurring in the afternoon. Besides, deflections occurring in the N–S direction or the vertical direction which change in magnitude and sense at different times of the day, could also alter the number of solar cosmic rays that are registered by an apparatus at any particular time. Thus, an ionization chamber can record a larger number of solar cosmic rays during the morning than in the afternoon on account of the vertical force acting on the particles. This would in effect tend to produce an earlier maximum and a decrease of $M\phi^D$.

Before one can draw conclusions concerning the change of $M\phi^D$ that can be expected, it is necessary to consider the stiffness (P/z) on which depends the curvature of a trajectory of a particle of momentum P and charge "z." The mean momentum $\bar{P}$ of primary particles whose secondaries are measured by the apparatus, changes with latitude and elevation of the station and with inclination of the sun during the day on account of alteration of the atmospheric path length for solar cosmic rays. $\bar{P}$ can also depend on the absorber used with the apparatus. It is difficult to estimate changes of $\bar{P}$ with latitude, elevation, and time as the true path length in the atmosphere depends on the

direction of incidence of a deflected trajectory and not on one along an optical path from the sun. Therefore, unless the trajectories are calculated, one cannot proceed far on quantitative lines. Broadly speaking, it is nevertheless possible to consider that the stiffness increases with increase of latitude, but decreases with increase of elevation of the place of observation or with proximity to noon local time.

Taking into consideration the change of stiffness and of R_x and R_z, one expects that the hour of maximum would become later with increase of latitude and the geomagnetic effects should get magnified at high elevations.

(a) The Latitude Dependence of $M\phi^D$

Experimental evidence on this point is meager. It is obviously necessary to compare only those results which have been obtained under similar experimental conditions and where similar corrections are applied to the data. The Carnegie Institution studies at Huancayo, Christchurch, Cheltenham, and Godhavn as reported by Lange and Forbush,[10] furnish the most reliable data for this purpose. The mean diurnal variation for the

TABLE VI. Latitude dependence of $M\phi^D$.

Station	Geo. lat.	Geomag. lat.	Elevation	$M\phi^D$
1 Huancayo	12°S	1°S	3350 m	$\pi-15°$
2 Christchurch	43°S	49°S	0	$\pi+41°$
3 Cheltenham	39°N	50°N	0	$\pi+38°$
4 Godhavn	69°N	80°N	0	$\pi+36°$

period 1939 to 1946 has hours of maximum at the different stations as shown in Table VI. It will be noticed that there is qualitative agreement with our expectation concerning $M\phi^D$ at low and high latitudes.

In the past, the occurrence of a maximum much later than noon at stations in high latitudes has been difficult to understand, for it was thought that positive solar cosmic rays can only be deflected towards the east. If a deflection towards the west at higher latitudes is indeed responsible for a maximum in the afternoon, the change of $M\phi^D$ with variation of stiffness at any particular latitude should take place in opposite directions at low and high latitudes. The stiffness can decrease with elevation, or there can be long term changes in the mean momentum of primary solar cosmic rays. For change of either kind, an increase of stiffness would displace the maximum nearer noon. Thus at low latitudes, $M\phi^D$ which is less than π, would increase and at high latitudes, $M\phi^D$ which is greater than π, would decrease.

This leads us to a new and a serious difficulty. We have shown elsewhere[5] by an examination of the Carnegie data that long-term changes of $M\phi^D$ are

[10] I. Lange and S. E. Forbush, Carnegie Inst. Wash. Publ. 175 (1948).

similar at all stations. If these are due to changes in the mean momentum of primary rays, we shall have to look elsewhere for an explanation of the late maxima that have been observed at stations in medium and high latitudes.

In connection with the latitude dependence of $M\phi^D$, Hogg's[11] data without external temperature correction and obtained with an ionization chamber at Canberra, are probably comparable with the Carnegie data. For $\lambda = 35°S$ and geomagnetic latitude $45°S$, we have for the years 1936 to 1940 a mean $M\phi^D = \pi + 38°$. This agrees well with the hour of maximum at Cheltenham, Christchurch, and Godhavn.

Thompson[12] has attempted to survey the change of the diurnal variation with change of latitude, in the Pacific. Thompson's data extend over a large range of latitudes but cover a very short period of time in each belt of latitude. He has reported that the amplitude and hour of maximum of the diurnal variation do not change significantly with latitude. However, we are inclined not to attach much weight to this result which is in contradiction to the Carnegie results of much greater reliability.

Geiger counter studies with vertically pointing telescopes have been made in London by Duperier[13] and by workers of our group[3,4] at Ahmedabad and Kodaikanal. Though the studies at London and in India have not been carried out with apparatus of identical design, the change of $M\phi^D$ follows broadly the pattern of the Carnegie studies.

(b) Directional Dependence of $M\phi^D$

We have discussed earlier the change in the sign of R_y, the force along the N–S direction, as the sun crosses the meridian plane. An important consequence of this is that in the northern hemisphere during the morning, solar cosmic rays would be preferentially recorded by a north-pointing telescope. However, in the afternoon, the rays would be preferentially recorded by a south-pointing telescope. Thus, the N telescope would show an earlier maximum of intensity than a S telescope and $(M\phi^D)_N$ should be less than $(M\phi^D)_S$. These conditions are expected to interchange in the southern hemisphere.

The directional studies of Alfven and Malmfors[14] at Stockholm, of Kolhörster[15] at Berlin, and of Elliot and Dolbear[16] at Manchester exhibit between the N and S telescopes just the type of difference in $M\phi^D$ that is expected qualitatively from the above considerations. At Stockholm, the difference in $M\phi^D$ in the two directions is about 80° as compared to the much smaller difference of about 28° at Manchester. This may result at least partly, from a larger value of R_y at the former place due to a higher latitude. Detailed comparison is however difficult because of dissimilarities in the telescopes used at the two stations. No experimental results are available from high southern latitudes, but it would be worthwhile to test if $(M\phi^D)_S$ is less than $(M\phi^D)_N$ as predicted here.

DISCUSSION

The most unsatisfactory aspect of the present analysis of the effect of the geomagnetic field on solar cosmic rays is that we neglect the contribution of particles of low momenta which suffer the greatest deflection. However, the qualitative analysis that is made here under a number of simplifying assumptions suggests a geomagnetic interpretation for the rather puzzling results of directional cosmic-ray studies.

We have earlier[4] expressed the view that the N–S difference curve may indicate little more than an arithmetic difference between the daily variation caused by secondaries of anisotropic cosmic rays measured in the N and S directions. Since a possibility has been shown here of explaining the observed facts in terms of geomagnetic effects, we might perhaps be able to get over the difficulties of the interpretation proposed by Elliot and Dolbear[17] wherein there is the necessity of a magnetic field in the space surrounding the sun.

It is now clearly necessary to pursue rigorously the theoretical problem of the geomagnetic effects on charged solar cosmic rays in order to get a fundamental insight into the daily variation of cosmic rays.

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