Influence of the Solar Magnetic Field Upon Cosmic Rays

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The heliomagnetic field has a considerable influence on the intensities of cosmic rays as measured upon the earth in high magnetic latitudes and elevations. The difference of intensities (integrated over the whole atmosphere) between Omaha and Saskatoon is decreased by it to the extent of about 50 percent. Diurnal and annual variations of the solar effect are calculated. They lie below or just on the verge of the present experimental error.

1. INTRODUCTION

SPECTROSCOPIC evidence points to the existence of a general magnetic field upon the sun, similar to the geomagnetic field of the earth.[1] Although the fact in itself is generally accepted, the numerical value of the solar magnetic dipole is subject to some uncertainty. The estimates of the strength of field H_p at the magnetic poles of the sun, based on the measured Zeeman effects of various lines of the solar spectrum, range from 10 to 50 gauss; the most probable value is about 25 gauss.[2] With respect to the orientation of the dipole axis, it is estimated that its ecliptic polar distance is 6°. This is so small an angle that it is justifiable to neglect it for the purposes of this paper, and to take the axis as normal to the plane of the ecliptic.

The fact that the solar field may produce a measurable influence upon the cosmic-ray intensities as observed on the earth was first pointed out by Vallarta.[3] Although extremely weak beyond the orbit of the earth, it acts over enormous distances and may produce considerable deviations in the motions of the charged particles belonging to the cosmic radiation. Only particles of comparatively low energy are affected, so that the effect is observable only in high magnetic latitudes where the slow particles can pass through the barrier of the geomagnetic field. The very exact new data on the intensity of cosmic rays, obtained by Millikan and Neher (preceding paper) in Omaha and Saskatoon, make it desirable to discuss the bearing which the solar effect may have on these observations. Without attempting complete accuracy we propose, therefore, to carry the analysis sufficiently far to answer this question.

2. MEAN HELIOMAGNETIC EFFECT

We consider at first cosmic-ray particles of the momentum A moving *in the magnetic equatorial plane* of the sun (which practically coincides with the plane of the ecliptic, as was mentioned in Section 1). From which directions can these particles reach the earth? The answer is given by a familiar formula due to Störmer: if f is the moment of the magnetic dipole[4] and $\mathcal{R}$ the distance of the earth from the sun, the incidence of the particles is restricted to an angular interval limited by the angles $+\mu$ and $-\mu$, measured from the normal to the radius vector from sun to earth (direction of the apex), where μ is defined by

$$\cos\mu = f/A\mathcal{R}^2 - 2(f/A\mathcal{R}^2)^{\frac{1}{2}}. \qquad (1)$$

The conditions are more complicated for the rays moving at an angle to the equatorial plane. A thorough investigation of the cone to which they are limited is due to Lemaitre and Vallarta;[5] but so much accuracy is not required for the present estimate. In the way of a rough approximation we may take the limiting angle which the rays form with the apex to be μ in all directions. In other words, we assume that the incoming rays are restricted to a circular cone about the direction of the apex. The actual cone is not cir-

[1] G. E. Hale, F. H. Seares, A. Van Maanen and F. Ellerman, Astrophys. J. **47**, 206 (1918).
[2] The author is indebted to Dr. A. Van Maanen for a very instructive conversation about the most probable value.
[3] M. S. Vallarta, Nature **139**, 839 (1937).
[4] The charge e of the particle is included in the definition of the moment f; compare Eq. (3) below.
[5] G. Lemaitre and M. S. Vallarta, Phys. Rev. **50**, 500 (1936).

cular and has a somewhat smaller solid angle than the one assumed by us. The difference is, however, insufficient to affect materially our general conclusions or numerical estimates. It is clear from Eq. (1) that the opening of the assumed cone of incidence depends on the momentum of the rays. For very slow rays ($AR^2/f<3-2\sqrt{2}$) the equation has no real solution and the rays are completely turned back. As the rays become faster the cone gradually opens and is "completely opened" when $AR^2/f=1$: i.e., when the rays come from all directions.

The vertex of the cone lies, of course, in the point of observation which is located on the surface of the earth or close to it. Consequently, a portion or the whole of its opening may be cut off by the geometrical shadow of the earth. We define as the *mean solar effect* the one prevailing in the case when the earth surface is parallel to the axis of the cone, so that exactly one-half of the cone is screened off. The remaining half has then the solid angle $\pi(1-\cos\mu)$ representing the fraction

$$I_0=\tfrac{1}{2}(1-\cos\mu) \tag{2}$$

of the open half-space. This expression also represents the *intensity* of the rays in relative units integrated over the whole atmosphere.

For the numerical calculation we take: radius of earth orbit $R=1.50\times10^{13}$ cm, polar magnetic field of the sun $H_p=25$ gauss, radius of the sun $r_0=7.0\times10^{10}$ cm. The connection between H_p and our definition of the moment f is

$$f=eH_pr_0^3/2c, \tag{3}$$

where $e=4.77\times10^{-10}$ is the charge of the particles (electronic charge) and c the velocity of light. Numerically we obtain for the dipole $f=0.68\times10^{14}$ abs. units. On the other hand, the momentum A of very fast particles (over 10^8 volt in the case of electrons) is connected with their energy E by the relation $A=E/c$ or, when the momentum is expressed g cm/sec. and the energy in 10^9 electron volt, $A=5.30\times10^{-14}\ E$. The quantity entering into Eq. (1) becomes, therefore, $f/AR^2=5.69/E$, and the equation itself takes the form

$$\cos\mu=5.69/E-4.76/E^{\frac{1}{2}}. \tag{4}$$

A graphical representation of the intensities I_0 derived from this formula is given by the

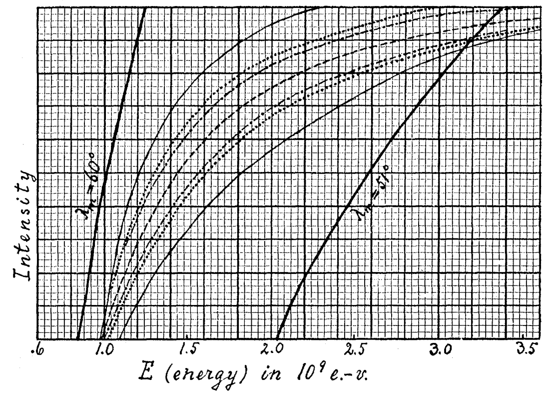

FIG. 1. Intensities of cosmic rays at various energies. Dashed curve, intensities from Eq. (4). Dotted curves, theoretical intensities; upper curve I_n, lower curve I_p; 4:50–5:40 P.M. August 14–17. Dash-dotted curves, theoretical intensities; upper curve I_p, lower curve I_n; 11:50 A.M. August 14–17. Light solid curves, theoretical intensities; upper curve I_p, 6 A.M., lower curve I_n, 6 P.M. June 21. Heavy solid curves, effect of geomagnetic field at Omaha ($\lambda_m=51°$) and Saskatoon ($\lambda_m=60°$).

dashed curve of Fig. 1. It will be seen from it that electron rays are completely eliminated by the solar field when their energies are below 1.0×10^9 ev, weakened in intensity in the range between 1.0×10^9 and 5.7×10^9 ev, and quite unaffected at higher energies.

3. Diurnal and Annual Variations

The part of the cone of incidence screened off by the surface of the earth changes with the daily rotation of this surface. This influence upon the intensities of cosmic rays must be investigated for two reasons: In the first place, it is necessary to make sure whether the quantity defined in Eq. (2) as the mean solar effect really sufficiently describes their intensity. In the second place, it is interesting to find out whether the diurnal and annual variations are large enough for observation.

We have not yet spoken about the direction in which the cosmic rays move in the cone of incidence. This direction depends upon the charge of the cosmic rays and upon the sense of the heliomagnetic dipole. Only the absolute value of the solar field (and not its sense) can be inferred by direct spectroscopic observations of solar lines. It is, however, surmised that the relation between the sense of the magnetic field and the sense of rotation is the same on the sun as on the earth. This means that the orientation of the solar dipole is such that the lines of magnetic force pass through the ecliptic from south to north. Consequently positively charged cosmic rays converge in the half-cone pointing in the apex of the earth motion (at noon to the west of the observer), while negative particles converge in the other half-cone.

Suppose that the vertical at the point of observation includes the angle $\pi/2-\zeta$ with the positive axis of the cone (i.e. direction of apex). An elementary geometrical calculation shows then that the unobstructed solid angle of the negative half-cone (divided by 2π) is

$$I_p=(1/\pi)\{\text{arc cos}\,(-\sin\zeta/\sin\mu)-\cos\mu\,\text{arc cos}\,(-\text{tg}\,\zeta/\text{tg}\,\mu)\},\quad \mu\geqslant\zeta\geqslant-\mu. \tag{5}$$

For $\zeta\geqslant\mu$, one obtains $I_p=1-\cos\mu$ and, for $\zeta\leqslant-\mu$, $I_p=0$. In all cases the unobstructed part of the positive cone (divided by 2π) is

$$I_n=1-\cos\mu-I_p. \tag{6}$$

If the influence of atmospheric absorption is neglected, the quantities I_p and I_n can be taken as measures of the intensities, respectively, in the two extreme cases when all the cosmic rays are positively charged and when they are all negatively charged. In the general case, when the fraction of the positive component is α and of the negative $1-\alpha$, the intensity has the expression

$$I=\alpha I_p+(1-\alpha)I_n=(2\alpha-1)I_p+(1-\alpha)(1-\cos\mu). \tag{7}$$

When positives and negatives are equally balanced $(\alpha=\frac{1}{2})$, this expression reduces to $I=I_0$ (mean solar effect).

There remains to find ζ as a function of the date and hour of observation. Let $\lambda_P(=66°\ 33')$ and n_P denote the ecliptic latitude and longitude (measured from the apex) of the North Pole of the earth. On the other hand, we may describe the positions of the point of observation (O) and of the apex (A) in a terrestrial system. It is easy to see that the geographical latitude λ_A of the apex is given by $\sin\lambda_A=\cos\lambda_P\cos n_P$, while we shall denote the geographical latitude of the point of observation by λ_0. The longitudes we shall measure from the noon meridian (i.e. the meridional plane passing through the sun). An elementary but somewhat lengthy calculation gives for the apex longitude

$$\varphi_A=-\pi+\text{arc cos}\left[\frac{\cos^2\lambda_P\sin n_P\cos n_P}{(1-\cos^2\lambda_P\sin^2 n_P)^{\frac{1}{2}}(1-\cos^2\lambda_P\cos^2 n_P)^{\frac{1}{2}}}\right] \tag{8}$$

an angle which is never greatly different from $-90°$, being contained between the limits $-90°\pm4°\ 56'$.

At the same time the longitude of observation in degrees is expressed by $\varphi_0=15t_0$, where t_0 is the local time in hours measured from noon. Consequently the angle $\frac{1}{2}\pi-\zeta$ between the local zenith and the apex is given by

$$\sin\zeta=\sin\lambda_A\sin\lambda_0+\cos\lambda_A\cos\lambda_0\cos(15t_0-\varphi_A). \tag{9}$$

We apply these formulas to the observations of Millikan and Neher carried out near Saskatoon (geographical latitude $\lambda_0=52°$, western longitude 107°) on August 14 to 17 of 1937. With sufficient accuracy we can take for the ecliptic longitude of the pole $n_P=38°$, obtaining

$$\lambda_A=18°\ 17',\quad \varphi_A=-94°\ 47'.$$

The data were obtained from three flights of sounding balloons at the following hours in mountain standard time: 11:50 A.M., 4:50 P.M., and 5:40 P.M. Formula (9) gives

M.S.T.	11:50 A.M.	4:50 P.M.	5:40 P.M.
t_0 (local time)	−0.30 hs.	4.70	5.53
ζ	14° 39′	−18° 34′	−19° 42′

The theoretical intensities for 4:50 and 5:40 P.M. are practically identical and are represented by the dotted curves of Fig. 1, the lower referring to I_p the upper to I_n. The dash-dotted curves give the intensities at 11:50 A.M. (upper curve I_p lower I_n).

A more favorable date for obtaining a large diurnal variation is June 21 (summer solstices) when $n_P=90°$ and $\sin\lambda_A=0$, whence $\sin\zeta=\cos\lambda_0\cos(15t_0-\varphi_A)$. At Saskatoon we find

M.S.T.	6:8 A.M.	6:8 P.M.
t_0	−6.00 hs.	+6.00
ζ	−38°	+38°

The intensities calculated from these data are represented by the light solid curves of Fig. 1. At 6 A.M. the upper curve gives I_p the lower I_n at 6 P.M. the conditions are reversed.

The *annual variation* can be treated much more simply than the diurnal. The eccentricity of the earth orbit is 0.0167 so that the distance from the sun varies in the course of the year by 3.3 percent. It is obvious from Eq. (1) that a change of distance in the proportion R'/R is compensated by a change of energy in the ratio $(R/R')^2$. An increase of distance of 3.3 percent produces, therefore, a shift of the intensity curves to the left, all the abscissae are decreased by 6.6 percent. The inclination of the heliomagnetic dipole also causes a slight variation of about 1 percent, but being semi-annual, this second effect does not change the difference between the extremes (which remains 6.6 percent of the abscissae) or the position of the extremes in time (maximum intensity about July 1, minimum about January 1). The annual variation affects positive and negative particles in the same way, but hardly ever attains an important numerical value.

4. Conclusions

For convenience we have also plotted in Fig. 1 the effect of the geomagnetic field in Omaha ($\lambda_m=51°$) and in Saskatoon ($\lambda_m=60°$). The solid lines so labeled give the intensities with which cosmic radiation components of various particle energies would pass through the terrestrial field in those two locations *in the absence of a solar field*. The diagram can be interpreted as referring to the imaginary case when the original energy spectrum is uniform, i.e., when the intensity outside the solar system plotted against the particle energy E is represented by a horizontal line—the top of the drawing. At the respective magnetic latitudes of 51° and 60° the earth field removes from these intensities everything to the left of the correspondingly labeled curves, so that the total intensities of the cosmic rays (barring the solar effect) are represented by the respective areas of the diagram to the right of these curves. The influence of the heliomagnetic field consists in the additional removal of the areas to the left and above the solar curves (which are explained in the preceding section). Therefore, the actual increase in total intensity between Omaha and Saskatoon should be equal to the area bordered, on the left and above, by the appropriate solar curve and, on the right, by the curve $\lambda_m=51°$.[6] The following conclusions can be drawn from this graphical representation.

(1) The upper limit of $H_p=50$ gauss, obtained for the heliomagnetic field from solar spectroscopy, is incompatible with cosmic-ray observations. In fact, Eqs. (1) and (3) show that an increase of H_p is equivalent to an increase of the the particle energies in the same ratio. If the field were 50 gauss instead of 25 gauss, as assumed in Fig. 1, the abscissae of all the solar curves should be doubled. This would move those lines entirely beyond the terrestrial curve for $\lambda_m=51°$, and leave no area between them. This means that, contrary to observations, there should be no increase of cosmic-ray intensity between Omaha and Saskatoon.

(2) The opinion was expressed by some astrophysicists that the general solar field is not constant but undergoes secular or periodic variations. If these variations are of any magnitude, they must have measurable counterparts in the cosmic-ray intensities in high magnetic latitudes and high elevations.

Assuming the heliomagnetic field at the poles to be $H_p=25$ gauss we may draw the following additional conclusions.

(3) The intensity difference between $\lambda_m=60°$ and $\lambda_m=51°$ is decreased by the solar field to about 50–60 percent of the value it would have in its absence.

(4) Because of the solar effect, the intensity increase with magnetic latitude stops at $\lambda_m=58°$.

(5) As the fractions of positives and negatives of the low energy particles are unknown, it is only possible to state what the diurnal effect would be if the sign of all particles were the same (compare Section 3). In this case, the change between 11:50 A.M. and 4:50 P.M. on August 16 (at Saskatoon) would amount to about $\frac{1}{3}$ of the mean measured intensity difference between Saskatoon and Omaha, or to about 2 percent of the total intensity observed in Saskatoon.

[6] Strictly speaking the curve $\lambda_m=51°$ should be reduced in the vertical direction so as to end on the solar curve; but this refinement is without practical importance.

(6) On June 21 the diurnal variation at $\lambda_m = 60°$ would amount to 4 percent or 5 percent or the mean total intensity (if all the particles had the same sign). In view of the mixed composition of the radiation the actual variation must be several times smaller.

(7) The annual variation at $\lambda_m = 60°$ is about 0.75 percent of the total intensity with its maximum on July 1 and its minimum on January 1.

At present variations of this magnitude are within the experimental error or just on its verge, but in a few years they may fall outside its range.

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The Loss of Neutrons by Neutron Bombardment and the Radioactive Isotopes of Scandium

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The bombardment of lithium by deuterons of 6.3 Mev energy yields neutrons of energy up to 20 Mev. These neutrons are in turn able to produce disintegrations by the ejection of two neutrons from bombarded nuclei. In the case of scandium there has been evidence that the process corresponding to the ejection of three neutrons also occurred thus producing Sc^{43} of half-life 4 hours and Sc^{44} of half-life 53 hours from the stable Sc^{45}. By varying the energy of the incident neutrons and observing the ratio of the two radioactivities produced, it now appears that these two activities are due to isomers of Sc^{44}. Hence there is no definite evidence as yet for the loss of three neutrons from the excited nucleus. Although scandium has but one stable isotope (Sc^{45}) there appears to be eight radioactive periods, six of which can be assigned with reasonable certainty to various scandium isotopes. The excitation function for the ejection of two neutrons is studied by observing the radioactivity produced at various energies of the incident neutrons. There is evidence of anomalous behavior for certain elements.

It has been shown[1] that most elements when bombarded by the energetic neutrons from lithium, yield isotopes corresponding to the ejection from the excited nucleus of two neutrons $(n, 2n)$. The beta-activity of isotopes so formed is usually positive in sign due to their position with respect to the stable isotopes. The energy required for this process might reasonably be expected to be in excess of 8 Mev. This follows from the equation representing the reaction:

$$_zA^N + n \rightarrow {}_z{}^*A^{N-1} + 2n \rightarrow {}_{z-1}A^{N-1} + {}_{+1}e + 2n.$$

Since $_zA^N$ and $_{z-1}A^{N-1}$ often differ by almost one mass unit, the energy of the positron and that corresponding to the excess mass of the second neutron (i.e. 0.0089 mass unit or 8.4 Mev) must be carried into the nucleus by the incident particle. The identification of the radioactive isotopes can be made reasonably certain by producing them by alternative methods in conjunction with the chemical analyses.

In certain elements, notably fluorine, copper and scandium radioactive isotopes lighter than the lightest stable isotope both by one and by two mass units have been identified. Thus in fluorine the stable isotope is F^{19} and the radioactive isotopes F^{17} and F^{18} have half-lives respectively of 1.2 min. and 109 min. In copper the lightest stable isotope is Cu^{68} and the radioactive Cu^{66} and Cu^{67} have half-lives of 3.4 hr. and 10 min. Scandium has a single stable isotope Sc^{45} and radioactive Sc^{43} and Sc^{44} of half-lives 4 hr. and 53 hr., respectively. The identification of these radioactive isotopes offers the possibility of detecting a process in which three neutrons are ejected from the nucleus excited by neutron bombardment $(n, 3n)$.

Positive results of this nature in the case of scandium have been reported.[2] This conclusion was based upon the correctness of the assignment of the radioactive periods of this element by Walke.[3] Table I shows the stable and radioactive

[1] Pool, Cork and Thornton, Phys. Rev. **52**, 239 (1937).

[2] Pool, Cork and Thornton, Phys. Rev. **52**, 41 (1937).

[3] H. Walke, Phys. Rev. **52**, 669 (1937); **52**, 777 (1937).