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An Apparent Effect of Galactic Rotation on the Intensity of Cosmic Rays

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Doppler effect studies of the globular clusters and the extra galactic nebulae have shown a motion of the earth of about 300 km/sec. toward about declination 47°N and right ascension 20 hr. 40 min., which is due chiefly to the rotation of the galaxy. Calculation shows that because of this motion the intensity of cosmic rays at sea level on an unmagnetized earth should be about 1.2 percent greater on the front side than on the back. Taking into account the earth's magnetic field, it is estimated (assuming the cosmic rays reaching the earth to consist of protons and electrons) that the diurnal variation at latitude 45° due to this motion should be, within a factor of 2, equal to 0.1 percent, with its maximum at 20 hr. 40 min. sidereal time. Data published by Hess and Steinmaurer show a sidereal time variation having just this amplitude and phase. While this agreement gives a strong presumption that the cause of this sidereal time variation is the earth's motion through space, another possible explanation is also considered. Experimental methods for making a definite test are outlined. The implication of a galactic rotation effect would be that the cosmic rays originate beyond our galaxy.

DR. HOWARD LOWRY has called our attention to the possibility that the motion of the earth through space may appreciably affect the intensity of cosmic rays. If these rays approach the earth from a source external to the galaxy, the effect due to our motion with the rotation of the galaxy should be perceptible, and comparison with existing cosmic-ray data shows a sidereal diurnal variation of just the anticipated type. If further experiments show this variation to be really due to the galactic rotation we shall have direct evidence of the very remote origin of cosmic rays, and a new method of determining the state of the earth's motion relative to the rest of the universe.

According to data kindly supplied us by Professor J. H. Oort, the rotational motion of our portion of the galaxy is in the galactic plane, directed toward 20 hr. 55 min. right ascension and 47°N declination, with a probable error of a few degrees. The most precise estimate of the speed has been made from the Doppler shifts of 18 globular clusters,[1] giving 275±50 km/sec. Observations of the Doppler effect of extragalactic systems give 380±110 km/sec. velocity in about the same direction.[2] Other methods give nearly the same result. In addition, the sun has a small individual motion of about 20 km/sec. The resultant velocity should be toward about $\alpha=20$ hr. 40 min., $\delta=+47°$ at about 300 km/sec. It would appear from the analysis by Oort[2, 3] of the motions of the remote galaxies, that the peculiar velocities of these systems are probably smaller than 80 km/sec. This means that if the cosmic rays come uniformly from all parts of the remote cosmos, our speed relative to their source is probably about that of the galactic rotation.

This motion with a speed of about 0.1 percent that of light will affect the intensity of the in-

[1] C. Strömberg, Astrophys. J. **61**, 357 (1925).
[2] E. Hubble, Proc. Nat. Acad. Sci. **15**, 270 (1929).
[3] J. H. Oort, Bull. Ast. Inst. Netherlands **6**, 155 (1931).

coming cosmic rays by changing both the energy of the cosmic-ray particles and the number received per second. Imagine, as in Fig. 1, the earth moving along AB with a speed βc, where $\beta \ll 1$, and imagine cosmic-ray particles with a speed γc, almost equal to that of light, moving in the direction CB, at an angle θ with the direction of the earth's motion. By making use of the relativity expressions for addition of velocities and for kinetic energy, it can then be shown that the energy of each particle relative to the moving earth is, to the first order of small quantities,

$$E' = E(1+\alpha\beta(\sqrt{2}-1)\cos\theta)/(1-\beta\cos\theta), \quad (1)$$

where E is its energy relative to an observer at rest, and $\alpha \equiv 1-\gamma$. If $\alpha \ll 1$, we may thus write without sensible error,

$$E' = E/(1-\beta\cos\theta). \quad (2)$$

If E is equated to $h\nu$, this becomes the usual expression for the Doppler effect with light.

To calculate the increase in the rate at which the cosmic-ray particles impinge on unit surface drawn normal to the direction of motion AB, let $AC = \gamma c$ be the distance traveled by a particle in unit time. Then to the first order of β the time required for a particle from C to reach B is

$$\tau = (\gamma c - \beta c\cos\theta)/\gamma c = 1-(\beta/\gamma)\cos\theta,$$

or, again by neglecting $1-\gamma$ when multiplied by β,

$$\tau = 1-\beta\cos\theta. \quad (3)$$

Assume for convenience a constant number of particles per unit path. The number striking a stationary unit surface at B within a range of directions $d\theta$ and in the time interval τ is then proportional to

$$n = (1-\beta\cos\theta)\cdot\cos\theta\cdot 2\pi\sin\theta d\theta, \quad (4)$$

while during the same interval the number striking the surface moving from A to B is

$$n' = 1\cdot\cos\theta'\cdot 2\pi\sin\theta d\theta. \quad (5)$$

From Fig. 1, however to the first order of β,

$$\sin\theta = \sin\theta'/(1-\beta\cos\theta')$$

and $$d\theta = d\theta'/(1-\beta\cos\theta').$$

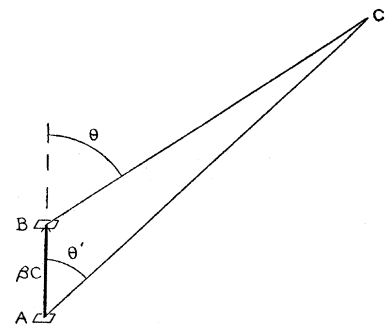

FIG. 1.

Thus by Eq. (5),

$$n' = \cos\theta'\cdot 2\pi\sin\theta' d\theta'/(1-\beta\cos\theta')^2, \quad (6)$$

where the primed angles are those observed from the moving surface. Within the same observed range of angles, therefore, the rate of receiving particles is thus increased by the motion in the ratio

$$n'/n = 1/(1-\beta\cos\theta)^3. \quad (7)$$

Since the intensity is the energy of the particles received per second per unit area, on combining Eqs. (7) and (2) we have, for the rays incident at an angle θ with the direction of motion,

$$I'/I = 1/(1-\beta\cos\theta)^4. \quad (8)$$

This is the counterpart of the fact previously shown by one of us[4] that the Doppler change in intensity of light from a moving source is equal to the 4th power of its change in frequency.

With coincidence counting tubes, arranged to record the radiation from a narrow range of directions, we should be concerned, except for the absorption by the atmosphere, with Eq. (7). With an ionization chamber it is the average effect from all angles with which we are concerned. Let us suppose that the direction of motion is toward the zenith (condition for maximum intensity). We may then weight roughly the contribution from the various directional zones by assuming to a sufficient approximation that when measured near sea level the intensity of the rays per unit solid angle falls off because of atmospheric absorption about as $\cos^2\phi$, where ϕ is the zenith angle. The number of particles received from the direction zone ϕ to $\phi+d\phi$ will

[4] A. H. Compton, Phys. Rev. **21**, 490 (1923).

thus be proportional to

$$\cos^2\phi\cdot 2\pi\sin\phi d\phi. \tag{9}$$

The mean energy of the incident particles is thus

$$\bar{E}'=\frac{\int_0^{\pi/2}E'\cos^2\phi\sin\phi d\phi}{\int_0^{\pi/2}\cos^2\phi\sin\phi d\phi}. \tag{10}$$

By writing Eq. (2) in the form

$$E'=E(1+\beta\cos\varphi), \tag{11}$$

its equivalent to the first power of β, we obtain on integration of Eq. (10)

$$\bar{E}'=E(1+\tfrac{3}{4}\beta). \tag{12}$$

At the surface of the atmosphere with an isotropic distribution of the rays, the ratio of the intensity in the moving system to that in the stationary system should similarly be, by Eq. (8):

$$\frac{I_0'}{I_0}=\frac{\int_0^{\pi/2}[2\pi\sin\theta d\theta/(1-\beta\cos\theta)4]}{\int_0^{\pi/2}1\pi\sin\theta d\theta}=1+2\beta, \tag{13}$$

to the first power of β.

The ionization observed in an ionization chamber depends, however, upon the fraction of the energy which penetrates the atmosphere and the fraction absorbed within the chamber. We may assume that the intensity is a function of the depth z below the surface of the atmosphere such that

$$I/I_0=f(z)\,; \tag{14}$$

but when the energy of the incident particles is increased by the factor $(1+\epsilon)$ the intensity follows a new function of the depth,

$$I'/I_0'=f_1(z)=f(z/(1+a\epsilon)). \tag{15}$$

This says that the "penetrating power" has been increased by a factor $(1+a\epsilon)$, a conception which may be strictly valid for exponentially absorbed particles, but expresses only roughly the effect of the increased energy on "range" particles. Since $-dI/dz$ is the energy per second spent per cm^3 as the rays traverse the atmosphere, the rate of ionization per cm^3 of the air is

$$i=-kdI/dz, \tag{16}$$

where k is the number of ions produced per unit energy (about 30 ions per electron volt), and i is nearly proportional to the ionization current measured in an ionization chamber. From Eqs. (15) and (14) we have thus for the ratio of the ionization observed on the moving earth to that on the earth at rest,

$$\frac{i'}{i}=\frac{dI'/dz}{dI/dz}=\frac{I_0'}{I_0}\frac{(d/dz)f[z/(1+a\epsilon)]}{(d/dz)f(z)}=\frac{I_0'}{I_0}\frac{1}{1+a\epsilon}\frac{f'[z/(1+a\epsilon)]}{f'(z)}. \tag{17}$$

We may write

$$f'[z(1+a\epsilon)]=f'(z-\delta z),$$

where $\delta z=a\epsilon z$. Also

$$f'(z-dz)=f'(z)-(d/dz)f'(z)\delta z\quad[\delta z\ll z]$$
$$=f'(z)-f''(z)\delta z.$$

Thus

$$f'[z/(1+a\epsilon)]/f'(z)=1-[f''(z)/f'(z)]\delta z$$
$$=1+m\delta z$$
$$=1+ma\epsilon z,$$

where

$$m\equiv -f''(z)/f'(z). \tag{18}$$

Eq. (17) may thus be written

$$i'/i=(I_0'/I_0)(1+ma\epsilon z)/(1+a\epsilon)=(I_0'/I_0)[1+a\epsilon(mz-1)]. \tag{19}$$

According to Eq. (12) we may use $\frac{3}{4}\beta$ for ϵ, and Eq. (13) gives the value of I_0'/I_0 as $1+2\beta$. The effective value of a cannot differ greatly from 1. With these values, expression (19) becomes to the first power of β,

$$i'/i=1+(5/4)\beta+(3/4)\beta mz, \tag{20}$$

or for the fractional change in intensity

$$\delta i/i=(i'-i)/i=\beta(5/4+(3/4)mz). \tag{21}$$

In this expression, as we have seen, β is presumably about 0.001, z is the depth below the surface of the atmosphere, and m, defined by Eq. (18) may be calculated from the experimental ionization *vs.* depth curve for any value of z.

Using the depth ionization data collected by

Eckart,[5] we calculate from Eqs. (18) and (21) the values of m given in Table I and of $\delta i/i$ for

TABLE I. *Predicted amplitude of variation of intensity at various depths, due to motion of $\beta=0.001$. (Eq. (21).)*

Depth ($kg/cm^2=z$)	I (ions)	m	$\delta i/i$
0.3	126	5.5	0.002
0.5	31	8.6	.004
0.7	9.1	9.0	.006
1.0	2.9	6.3	.006
1.5	1.54	4.4	.006
2.0	1.03	1.8	.004
3.0	.61	1.7	.005

various depths below the surface of the atmosphere. In the neighborhood of sea-level ($1\ kg/cm^2$), this means a difference of 1.2 percent between the front and the back sides of the earth.

There are, however, two factors which must prevent observing this full effect, the deflection of the cosmic-ray particles by the earth's magnetic field, and the inclination of the earth's axis relative to the motion in question. If δ is the declination of the direction of motion, λ the latitude of the observer and θ the hour angle between the observer's meridian and the direction of motion, then the angle ϕ between the observer's zenith and the direction of motion is given by

$$\cos\phi=\sin\delta\sin\lambda+\sin\delta\cos\lambda\cos\theta. \quad (22)$$

The factor by which the predicted variation should be reduced is

$$F=\tfrac{1}{2}(\cos\phi_{\text{max.}}-\cos\phi_{\text{min.}}). \quad (23)$$

The best available data for testing the prediction have been collected by Hess and Steinmaurer[6] on the Hafelekar, at an altitude of 2300 meters and a latitude 47°N. At this station, by Eqs. (22) and (23), we get $F=0.496$.

The effect of the magnetic field cannot be calculated with precision. If we assume the composition of the cosmic rays suggested by one of us,[7] the rays reaching the earth consist of a penetrating component of protons, and a less penetrating component of electrons, apparently about equally divided between positrons and negatrons. The protons and electrons seem to comprise about 40 percent and 60 percent, respectively, of the rays as observed at 2300 meters. The protons constitute the rays which show a latitude effect at 47 degrees, and are thus strongly bent by the earth's magnetic field. Protons of each energy should show a maximum at a different sidereal time, and these times will be distributed throughout the entire 24 hours. It is unlikely therefore that this component can contribute appreciably to a diurnal variation. The electron component on the other hand must have such great energy to traverse the atmosphere that its curvature should be considerably less. If, as Johnson's new results seem to show,[8] there are about equal numbers of positrons and electrons, the magnetic curvatures will diffuse the rays in both directions, thus lessening the diurnal variation, but will not alter the phase of the maximum. A reasonable estimate would seem to be that the variation due to this component should be between 10 percent and 50 percent as great as if they were undeflected. Taking these various factors together, we may anticipate a total diurnal variation under the conditions of Hess and Steinmaurer's experiments, within perhaps a factor of 2, equal to 0.1 percent. Its maximum should most probably occur close to the sidereal time, 20 hr. 40 min., when the earth's motion is toward the zenith.

This calculation is directly comparable with the experiments of Hess and Steinmaurer,[6] in which the average results of a complete year of observations, after making the necessary corrections, have been plotted against the sidereal time. In Fig. 2, are shown: (1) the effect as predicted above, of 0.05 percent amplitude and with its maximum at 20 hr. 40 min. sidereal time; (2) Hess and Steinmaurer's data averaged over half-hour periods, taken from their Fig. 5; and (3) the same data averaged over 3-hour periods. It will be seen that there is a definite sidereal time variation whose phase and amplitude are very close to those predicted. A least-squares analysis of these data, kindly carried through for us by Mrs. Ardis T. Monk, gives for the first harmonic an amplitude of $0.043\pm.0045$ percent with its maximum at 21 hr. 31 min. ± 23 min. Thus the effect is almost 10 times the probable

[5] C. Eckart, Phys. Rev. **45**, 851 (1934).
[6] V. F. Hess and R. Steinmaurer, Sitzungsber. Preuss. Ak. Phys.-Math. Kl. **15** (1933).
[7] A. H. Compton, Proc. Phys. Soc. London, April, 1935. A. H. Compton and H. A. Bethe, Nature **134**, 734 (1934).
[8] T. H. Johnson, Phys. Rev. in press (1935).

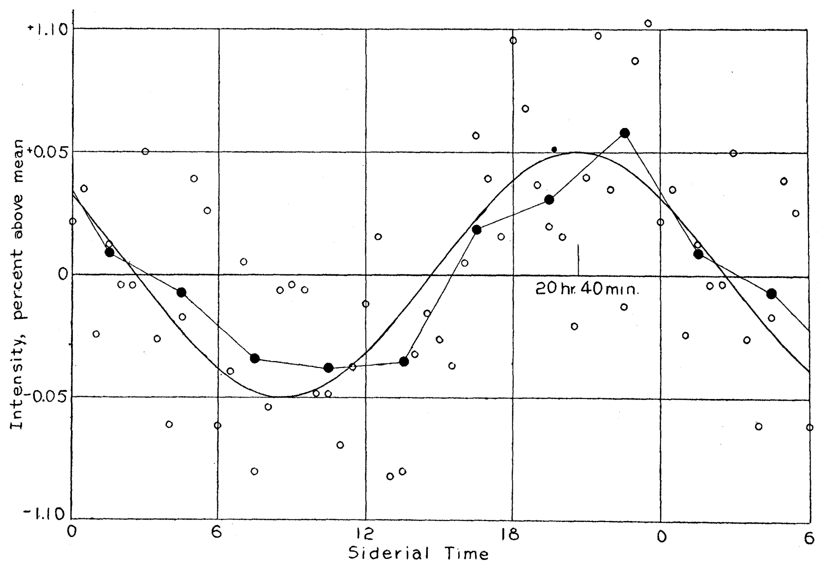

FIG. 2. Percentage variation in intensity of the cosmic rays with sidereal time. Curve, predicted effect due to galactic rotation. Data, Hess and Steinmaurer; open circles, half-hour means; solid circle, 3-hour means.

error, and cannot therefore be ascribed to chance.

No other data of such precision are available which are suitable for testing this sidereal diurnal effect. In the records of Steinke for 1929[9] little if any effect is evident, whereas his data for 1926[10] seem to show about the same magnitude of effect as those of Hess and Steinmaurer.

Messerschmidt has pointed out that if the solar diurnal variation differs at different seasons of the year, the annual mean will show an apparent sidereal time variation. It should be possible to test this suggestion in two ways. (1) Measurements of the same type as those of Hess and Steinmaurer, if made in the southern hemisphere, should show a sidereal time variation due to the earth's motion with its maximum at the same sidereal time. If, however, the effect is due to a seasonal difference in the solar time variation, the apparent sidereal maximum in the annual mean as observed in the southern hemisphere should differ in phase by 12 hours as compared with the northern hemisphere. (2) There should be a difference in the cosmic-ray intensity in the northern and southern hemispheres due to the earth's motion. Since the earth's magnetic field does not bend the approaching rays from the northern to the southern hemisphere, or *vice versa*, we may expect this difference to be almost as great as if no magnetic field were present. According to Eq. (22), the 24 hour mean of the component of motion in the direction of the zenith is proportional to sin δ sin λ. For northern and southern stations at 45° latitude, and taking δ as $+47$ degrees, this means that the average intensity at the northern station should be, according to Table I, about 0.6 percent greater than at the southern station. Though existing data are not of sufficient precision to show this difference, the predicted effect is of sufficient size to be measurable with some precision by using the more refined meters now in use.

While we must await some such measurements before we can consider the effect due to the rotation of the galaxy as established, the quantitative agreement with the predictions as shown in Fig. 2 gives a strong presumption in its favor. Its existence would imply that an important part of the cosmic rays originates outside of our galaxy. If its magnitude is found to be as great as we have predicted, it will imply that practically all the cosmic radiation has an extragalactic origin.

[9] E. Steinke, Zeits. f. Physik **42**, 570 (1927).
[10] E. Steinke, Zeits. f. Physik **64**, 48 (1930).