II. Time Variations of Cosmic Rays

The Significance of Variations in Cosmic-Ray Intensity and Their Relation to Solar, Earthmagnetic and Atmospheric Phenomena

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THE opinion held by several prominent physicists in former years that the intensity of cosmic radiation before entering the upper atmosphere is constant, always opposed by the writer, has been abandoned completely on account of new experimental evidence found at different stations[1] in North and South America, New Zealand and in Central Europe, in A. H. Compton's world-wide survey and at the Alpine Observatory on the Hafelekar (Austria) by the writer and his collaborators.

It has been proved that regular and irregular variations of the cosmic-ray intensity with time (after reduction to normal atmospheric pressure) certainly do exist and that part of these variations occurs simultaneously at different widely separated points of observation, distributed all over the globe. These world-wide changes are another unexpected proof of the extraterrestrial origin of these rays that will allow very interesting conclusions about relationship of cosmic-ray intensity with solar and geomagnetic phenomena.

I. SOLAR ACTIVITY AND ITS BEARING ON COSMIC-RAY INTENSITY

From all we know so far it must be considered as rather improbable that even a small percentage of the cosmic-ray corpuscles is emitted by the sun itself. On the other hand the solar magnetic field[2] tends to prevent charged particles below certain energy limits from reaching the earth and so has a definite influence upon the energy spectrum of the cosmic-ray particles even before they are deflected by the magnetic field of the earth.

Several years ago an extensive investigation was carried out by one of my collaborators[3] in order to find out whether a marked relation between solar activity (number and position of sunspots and of flocculi) and cosmic-ray intensity exists. From an analysis of our observations on the Hafelekar (2300 meters above sea level) near Innsbruck (Tyrol) during a three-year period (1932, 1933, 1934) only a very slight, negative correlation could be derived (correlation coefficient -0.48 ± 0.08).

Now since geomagnetic disturbances are not always connected with sunspots or with flocculi, but rather with other active regions on the sun (so-called M-regions) it was thought possible that an influence of these regions could be detected by dividing the entire observational material into groups according to the cycles of the sun's rotation. This procedure indeed met with success. From 45 successive 27-day cycles the presence of a rather regular variation of the cosmic-ray intensity within each cycle was proved. We found that the amplitude of this variation amounted to ±0.3 percent on the Hafelekar. Similar investigations with observations made later with Compton meters at Cheltenham (Maryland), 38° N, Teoloyucan (Mexico), 20° N, Huancayo (Peru), 12° S and Christchurch (New Zealand), 43° S corroborated the existence of a 27.9-day period in cosmic-ray intensity with an amplitude of about ±0.2 percent, as reported by Piara S. Gill.[4] The period of the sun's rotation relative to the earth varies from about 26 days at the sun's equator to 32 days at 80° solar latitude, with an average of 27.1 days. The opinion that the sunspots themselves are directly responsible for changes in cosmic-ray ionization, as expressed by Piara S. Gill cannot be held on account of the results of the above-mentioned investigations on the Hafelekar.

[1] See S. E. Forbush, Phys. Rev. **51**, 1108 (1937); A. H. Compton and R. N. Turner, Phys. Rev. **52**, 709 (1937); V. F. Hess, Terr. Mag. **41**, 345 (1936); V. F. Hess, R. Steinmaurer and A. Demmelmair, Nature **141**, 686 (1938).

[2] L. Janossy, Zeits. f. Physik **104**, 430 (1937); P. Epstein, Phys. Rev. **53**, 862 (1938).

[3] H. Graziadei, Wien Sitz. Ber. II*a*, **145**, 495 (1936); V. F. Hess, Terr. Mag. **41**, 345 (1936).

[4] Piara S. Gill, Phys. Rev. **55**, 429 (1939); see also S. E. Forbush, Terr. Mag. **43**, 217 (1938).

II. Correlation Between Cosmic-Ray Intensity and the Earth's Magnetic Field

It is well known that at the beginning of a magnetic storm the horizontal magnetic field intensity is rapidly decreasing ("sudden commencement"). Changes of more than 100γ ($1\gamma = 10^{-5}$ gauss), equivalent to 0.5 percent of the total horizontal intensity are frequent. The nature of these changes is such that they can be ascribed to a ring-shaped westward electric current system flowing in the plane of the geomagnetic equator or to a spherical current sheet, concentric with the earth, high in the upper atmosphere or in the outer space.

During several severe magnetic storms in 1937 and 1938 S. E. Forbush[5] and V. F. Hess and A. Demmelmair[6] found a very pronounced positive correlation between the intensity changes of cosmic rays and of the magnetic horizontal force. This indicated that during severe magnetic disturbances world-wide variations of the cosmic-ray intensity occur ("magnetic storm-effect"), as observed simultaneously in North America, Peru and Central Europe. S. Chapman[7] has offered an explanation of this large "positive" storm effect on the basis of Stoermer's hypothesis that part of the earth's axial magnetic moment is caused by electronic ring currents flowing at distances of several earth radii concentrically around the earth. If during a solar outburst these electric ring currents are increased, the magnetic dipole moment of the earth is strengthened for regions outside of these ring currents while inside, near the surface of the earth, the magnetic horizontal force is reduced. The increase of the earth's magnetic field in the outer space produces an increased deflection of the paths of the cosmic-ray particles, thus reducing the observed cosmic-ray intensity on the earth. Chapman[7] and also J. Clay and E. M. Bruins[8] calculated the radius of this ring current system and found it equal to about three earth radii. Clay and Bruins assumed that the ring currents are permanently in existence and that at the onset of a magnetic storm their intensity is diminished. They claim that only in this way the observed decrease of magnetic horizontal force can be explained.

It is interesting to note that aurora borealis has been observed several times at unusually low latitudes and at the same time a decrease of cosmic radiation was found.[9]

The "magnetic storm effect" on cosmic rays discussed here can be expressed quantitatively by the ratio of the relative change in cosmic-ray intensity $\Delta I/I$ and of the horizontal force $\Delta H/H$. Thus during a storm in April, 1937 this effect amounted to $\Delta I/I : \Delta H/H = 15$ and was almost equal in Cheltenham (U. S. A.) and Hafelekar (Austria). This relative magnitude of the effect was, however, found to differ considerably in different storms. S. E. Forbush[10] reported one case of a storm (August 21 to 25, 1937) where a decrease and a following increase of the horizontal magnetic intensity of 120γ were observed with almost no change of cosmic-ray intensity at three stations in Peru, Mexico and in the United States.

There is no doubt that world-wide simultaneous variations of 5 percent and more in cosmic-ray intensity do occur; some of these are strongly correlated with similar changes of the earth's magnetic horizontal force. On the other hand some magnetic storms have little, if any effect on the cosmic-ray intensity. Thus we could speak perhaps of magnetic storms as "effective" and "non-effective" in respect to cosmic-ray intensity. Forbush analyzed both types of storms and found that in either case the magnetic disturbance could be ascribed to ring current systems with different radii, having a magnitude of not less than two earth radii. The total intensity of the ring current was estimated as between 20,000 and 60,000 amperes.

A positive correlation between cosmic-ray intensity (daily mean values) and magnetic horizontal force has also been noticed during magnetically quiet periods ever and again in our observations on the Hafelekar[11] in 1933 and 1936/1937. If longer periods (one year) are summarized, however, the correlation is on the

[5] S. E. Forbush, Phys. Rev. **51**, 1108 (1937).
[6] V. F. Hess and A. Demmelmair, Nature **140**, 316 (1937).
[7] S. Chapman, Nature **140**, 423 (1937).
[8] J. Clay and E. M. Bruins, Physica **5**, 111 (1938).
[9] V. F. Hess, A. Demmelmair and R. Steinmaurer, see reference 1.
[10] S. E. Forbush, Terr. Mag. **43**, 203 (1938).
[11] V. F. Hess, A. Demmelmair and R. Steinmaurer, Wien Sitz. Ber. II*a*, **147**, 91 (1938).

whole negative and less pronounced. It seems as if two opposite magnetic effects on cosmic rays were superposed. From a purely statistical analysis we found that there is also a strong correlation between the diurnal variations of cosmic radiation and the horizontal force and also in the seasonal change of both quantities. In both cases the correlation is negative, i.e. a decrease of cosmic-ray ionization (I) is accompanied by an increase of H. The ratio of the relative variations of I and H was $\Delta I/I : \Delta H/H = -4$ in the case of the diurnal variation and $\Delta I/I : \Delta H/H = -22$ in the case of the seasonal changes.

It was pointed out, however, that it seemed rather unlikely—in spite of the strong correlation of $r = -0.75$—that the seasonal variation of I could be causally connected with the seasonal change of H.

Thomas H. Johnson,[12] too, is sceptical about the real meaning of these correlations. He pointed out that even close correlations between cosmic-ray intensity and terrestrial magnetism as mentioned above do not necessarily mean that the two quantities are causally related. He found by using the theory of Lemaître and Vallarta that in the case of the most pronounced storm effect the ring current hypothesis cannot account for the magnitude of the cosmic-ray change, which is about 100 times as large as could be expected from the observed change in the magnetic field, even if the most favorable case of a ring current system as close as possible to the earth, located in the upper atmosphere is assumed.[13]

On the other hand S. E. Forbush[10] calculated the radii and the intensities of the hypothetical ring currents around the globe both in the case of "effective" and "non-effective" magnetic storms and found that with the assumption of ring current radii between 2 and 16 earth radii the observed different effects on cosmic-ray intensity can be explained.

It seems to me that the assumption of rather wide ring currents has been useful, at least qualitatively, and that discrepancies may be explained by additional considerations. If we assume a ring current flowing in the equatorial plane, at a distance of a few earth radii around the globe, we must not forget that inside, for points near the surface of the earth the change of magnetic horizontal force may be considerably less than the percentage change of magnetic intensity in regions outside of the ring current: the lines of force, after traversing the equatorial plane inside the ring current spread out very considerably and their density (flux) will be very much less for points near the earth, north or south of the geomagnetic equator.

Furthermore it must be kept in mind that the core of the earth consists of highly paramagnetic elements. Thus a deflection of the magnetic lines of force must be expected: if the ring current is established the lines of force set up by this current will traverse the equatorial plane of the earth not with homogeneous density; lines of force, due to this current which would otherwise pass near the surface of the earth, parallel to the magnetic meridians will be deflected towards the core on account of its greater permeability and therefore the additional horizontal force due to the ring current will be found very much smaller than would be the case if the core were not strongly paramagnetic. We would accordingly expect a very small variation in the observed total horizontal force even when a very powerful ring current is set up.

It will be comparatively easy to make experimental determinations of the actual changes of the magnetic fields in- and outside the ring, by using a model of the earth with a ferromagnetic core and with conducting rings at different distances from it. It can be expected that the field inside the ring current is far from being

TABLE I. *Values of temperature effect.*

α (%/°C)	Point of Observation	Authors
−0.093	Innsbruck and Hafelekar (Austria)	V. F. Hess, H. Graziadei, R. Steinmaurer,[1] J. Priebsch, W. Baldauf,[2] 1932–1934
−0.12	South Africa (Cape Town)	B. F. J. Schonland, B. Delatizky, J. Gaskell,[3] 1933–1935
−0.18	Pacific Ocean	A. H. Compton, R. N. Turner[4] (1936)
−0.08	Hafelekar, Austria	A. Demmelmair,[5] 1936–1937

[1] V. F. Hess, H. Graziadei, R. Steinmaurer, Wien Sitz. Ber. IIa, **143**, 313 (1934); V. F. Hess, Terr. Mag. **41**, 345 (1936).
[2] J. Priebsch and W. Baldauf, Wien Sitz. Ber. IIa, **145**, 583 (1936).
[3] B. F. J. Schonland, B. Delatizky and J. Gaskell, Terr. Mag. **42**, 137 (1937).
[4] A. H. Compton and R. N. Turner, Phys. Rev. **52**, 709 (1937).
[5] A. Demmelmair, Wien Sitz. Ber. IIa, **146**, 643 (1937).

[12] Thomas H. Johnson, Rev. Mod. Phys. **10**, 229 (1938).
[13] Thomas H. Johnson, Terr. Mag. **43**, 1 (1938).

homogeneous and the field changes actually observed on the surface of the earth may be only a small fraction of the magnetic field changes set up by the ring current in its less remote neighborhood.

The actual amount of this fraction will vary with the diameter of the ring current. The great variability of $\Delta I/I : \Delta H/H$, as actually observed could be interpreted in this way.

III. The Temperature-Coefficient of the Cosmic Radiation and its Explanation by the Hypothesis of the Instability of the Mesotron

The observed decrease of the cosmic-ray intensity with increasing atmospheric temperature ("external temperature effect") was explained recently by P. M. S. Blackett[14] on the basis of the instability of the mesotron: with increasing temperature the atmosphere expands upwards and this causes an upward shift of the mesotron-producing layer. The mesotrons then have to travel further to reach sea level and on account of their limited life-period more of them decay the farther they have to travel. Thus a decrease of the radiation near the ground is quite conceivable.

If L denotes the "life-range" that is the distance which a mesotron could cover within its average life-period, then according to Blackett the temperature coefficient of the cosmic radiation $\alpha = -(1/I)(dI/d\theta) = (1/L)(dz/d\theta)$ where dz denotes the actual change in the height of the mesotron-producing layer during a temperature change of $d\theta$. Instead of $dz/d\theta$ the ratio of the average value $\bar{z}$ of the height of the mesotron-producing layer and of the average atmospheric temperature $\bar{\theta}$ can be taken: $\alpha = -(1/I)(dI/d\theta) = -(1/L)(\bar{z}/\bar{\theta})$. Taking H. Euler and W. Heisenberg's value for the mean life of the mesotron at rest, $\tau_0 = 2.7 \times 10^{-6}$ sec., $L = 32$ kilometers, $\bar{z} = 16$ km and $\bar{\theta} = 250$°K, Blackett calculated for α a value of -0.2 percent per degree centigrade. Using observed values of dz and $d\theta$ (Humphrey's) he obtained a similar value of $\alpha = -0.16$ percent per °C.

Some observed values of the temperature effect, as far as they are derived from sufficiently long series of observations are given in Table I. The agreement with Blackett's calculated values of α is apparently quite satisfactory.

There are, however, facts which do not fit so well into this picture: from the observations on the Hafelekar, cited above, a very definite and rather regular seasonal variation of the temperature coefficient has been found ever and again in five years of almost continuous registration of the cosmic-ray intensity (in all these observations the ionization chamber was shielded on all sides with at least 10 cm lead). These seasonal changes of α are rather large: in winter α is more than twice as large as in summer. Thus the variation of α during the year amounts to ± 50 percent of its average value. This would correspond, according to the formula given by Blackett, to a change in the average height of the mesotron-producing layer from 16 km to 24 and 8 km, respectively! It is well-nigh impossible to give any reason for such an enormous change in the mesotron-producing layer.

If we want to retain Blackett's interpretation of the temperature effect by the instability of the mesotron, we must conclude that the outdoor temperature near the ground which had to be used for the calculations of the observations is a very inadequate means of judging the temperature conditions of the whole vertical column of air above the point of observation. It seems that in winter this inadequacy is somewhat different than in summer and that, therefore, the differences in the temperature coefficient of the cosmic radiation in the course of each year are only apparent. This seems altogether the most feasible explanation of our discrepancy.

The actual magnitude of the temperature coefficient could, therefore be obtained only at a station where observations of the temperature of the atmosphere from the ground to great altitudes are carried out regularly beside the hourly registration of the cosmic-ray intensity near the ground.

The vertical extent of the thermal expansion of the atmosphere is, of course, somewhat uncertain. J. Barnóthy and M. Forró,[15] offering an explanation of the difference in sign and magni-

[14] P. M. S. Blackett, Phys. Rev. **54**, 973 (1938).

[15] J. Barnóthy and M. Forró, Phys. Rev. **55**, 868 (1939).

tude of the temperature effect in vertical and triangle coincidence counter arrangements cite meteorological evidence that the *daily* temperature changes do not extend over 1.5 to 2 km; the actual change of temperature in this column of air is assumed to decrease linearly with height. This would mean that if we take the temperature variations from readings near the ground we are assuming changes in the air column which may be twice as large as they actually are. Accordingly this would result in giving too low experimental values for the temperature coefficient of the cosmic radiation.

It must be emphasized, however, that the actual amount of the vertical expansion of a column of air of only 2 km height would not suffice to account for the temperature effect if we choose, for the life-period of the mesotron and its energy, values as used by Blackett and by Euler and Heisenberg: the upward expansion of a column of air of 2 km with rise of temperature of 1°C amounting to 7 meters would cause a decrease of only 0.02 percent in the number of mesotrons reaching the ground.

It is still to be kept in mind that Barnóthy and Forró's considerations are not applicable to variations of temperature from day to day during the year. These variations certainly are not restricted to the lowest regions of the atmosphere and all calculations of the temperature effect, as cited above, are in fact based upon such cases.

There is another discrepancy, yet to be explained: Blackett pointed out that at the equator where the incoming radiation is more energetic, the mesotrons would have greater energy and thus a longer life. Therefore the temperature coefficient near the equator should be lower than at higher latitudes. The numerical values of α, as given above, do not support this conclusion. It seems that our observations in the Tyrolean Alps (1932–1937) give smaller temperature coefficients than the ones at lower latitudes, in South Africa and on the Pacific Ocean. Determinations of the temperature effect on the Hafelekar (2300 m above sea level) and in Innsbruck (600 m above sea level) with the same apparatus gave the same results; therefore it is not possible to ascribe the rather low values of α obtained on the Hafelekar to the higher elevation of this station.

Further observations of the temperature effect in different latitudes seem to be necessary. It would also be advisable to carry out comparative registrations of the cosmic-ray intensity with a Steinke apparatus (as used in Tyrol) and a Compton apparatus at one station during one year, as I suggested already three years ago to several colleagues at the meeting of the International Geophysical Union in Edinburgh.