On the Seasonal and the Atmospheric Temperature Effect in Cosmic Radiation

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By analysis of the observations of the cosmic-ray ionization on the Hafelekar (2300 meters above sea level, 48° North geomagnetic lat.) during five years the existence of a seasonal variation with an amplitude of ±0.9 percent has been proved. Reduction of the monthly means to the annual mean temperature diminishes the amplitude of the 12-month wave to one-half without eliminating it. This agrees with Vallarta and Godart's interpretation of the seasonal effect. A very marked seasonal change in the temperature coefficient of the cosmic radiation has been found, recurring every year. In winter the coefficients are about −0.12, in summer −0.055 percent per degree centigrade. The correlation between temperature and ionization is in winter twice as great as in summer. Derivation of the temperature coefficient from hourly observations gives too low absolute values because of the diurnal changes involved. With unscreened ionization chambers and also with coincidence counter arrangements (triangle position), smaller temperature coefficients are found, which become positive in summer. It is thus not possible to explain the normal negative temperature effect of cosmic radiation completely on the basis of the mesotron disintegration hypothesis.

DURING the Symposium on Cosmic Rays in Chicago (June, 1939) I reported on some difficulties which arise with Blackett's otherwise so attractive interpretation of the atmospheric temperature effect on cosmic-ray intensity based on the mesotron disintegration hypothesis.[1] Meanwhile I have received additional experimental data through the courtesy of Fr. F. X. Roser (Rio de Janeiro), who sent me his thesis which had been worked out in Innsbruck in 1937 and 1938 under my supervision. This thesis contains the full, hitherto unpublished results of our cosmic-ray registrations in the Hafelekar Observatory (Tyrol), 2300 meters above sea level, up to the end of 1937. These data comprise now the fifth year of almost continuous cosmic-ray registration with the Steinke Standard apparatus (1932, 1933, 1934, 1936 and 1937) and enable me to discuss fully the whole complex of questions connected with the temperature effect on cosmic-ray intensity, using also results of other observations with apparatus of the same type with and without complete screening and observations with Geiger-Müller counters, published elsewhere by several of my collaborators.[2]

It is especially noteworthy that a qualitative interpretation of the temperature (air mass) effect is possible without resorting to the hypothesis of mesotron disintegration. I have in fact freely made use of such an explanation in our first publications on the temperature effect,[3] where the existence of this effect was proved beyond doubt.

The interpretation given at that time was to ascribe the increase of cosmic-ray ionization at lower temperatures (after correcting all values to standard pressure) to an enhanced scattering in the lowest part of the atmosphere, due to the increased density of air therein. It was, of course, not feasible to attempt a quantitative discussion of such an effect at that time, since I had no information on the mass distribution of air above the apparatus except that given by the air temperature near the ground.

I. The Seasonal Effect

The seasonal variation of cosmic-ray intensity (about 2 percent in the course of the year) is now a well-established fact,[4] and recent findings of W. P. Jesse[5] seem to indicate a seasonal variation of even greater range (10 percent) for the rays

[1] V. F. Hess, Rev. Mod. Phys. **11**, 153 (1939).
[2] J. A. Priebsch and H. Kramer, Anzeig. Wien, Akad. d. Wiss., Jan. 14, 1937; A. Demmelmair, Wien. Sitz. Ber. Akad. d. Wiss., **146**, 643 (1937); J. A. Priebsch and W. Baldauf, Wien. Sitz. Ber. Akad. d. Wiss. **145**, 583 (1936).
[3] V. F. Hess and R. Steinmaurer, Berlin. Sitz. Ber. **15**, 521 (1933); V. F. Hess, H. Graziadei and R. Steinmaurer, Wien. Sitz. Ber. **143**, 313 (1934).
[4] See V. F. Hess, H. Graziadei and R. Steinmaurer reference 3.
[5] W. P. Jesse, Rev. Mod. Phys. **11**, 167 (1939).

entering the higher parts of the stratosphere. For the lower parts of the atmosphere it is very difficult to state definitely whether the seasonal variations are entirely or partly due to the atmospheric temperature effect; what we know with certainty is only the existence of a rather close negative correlation between temperature near the ground and ray intensity. The correct way of finding out more about the existence of a real nonthermal seasonal effect of the cosmic rays is to analyze the magnitude of the temperature effect for shorter periods of, for instance, from one to three months and to compare the results with those obtained from analysis of observational data of one or more years. This was attempted by two of my co-workers[6] who found, using exact statistical methods (method of multiple correlation), that in 25 series of data consisting of the daily mean values of cosmic-ray intensity for one or two months the temperature coefficients from these shorter periods did *not* differ essentially from those derived from a whole year. This would indicate that on the Hafelekar, in 2300 meters above sea level, the seasonal variations are mainly due to the temperature effect. This would be in a way contradictory to a true seasonal effect in Jesse's stratosphere observations, but could be explained by assuming that only the softer part of the primary radiation is subject to the large seasonal change which he suspects.

It is very interesting to note that a seasonal effect was also found in the Southern Hemisphere by Schonland, Delatitzky and Gaskell[7] with the minimum cosmic-ray intensity in midsummer (January). It has been shown also by Schonland, Hess and their collaborators that the seasonal variation is greatly reduced but not completely eliminated when all monthly means are corrected for temperature effect.

TABLE I. *Seasonal variation of cosmic-ray intensity, Hafelekar (Tyrol), 2300 m above sea level, 1932 to 1937.*

Month	C.R. Intensity	C.R. Intensity reduced to annual mean temperature
I	2769 mI	2757 mI
II	2772 "	2757 "
III	2771 "	2755 "
IV	2764 "	2761 "
V	2728 "	2734 "
VI	2719 "	2731 "
VII	2725 "	2744 "
VIII	2723 "	2739 "
IX	2734 "	2746 "
X	2748 "	2741 "
XI	2756 "	2750 "
XII	2770 "	2761 "

Table I and Fig. 1 show the seasonal variation of cosmic radiation on the Hafelekar in an average taken from five years of observations (1932–1934, 1936, 1937). These data, hitherto unpublished, are all reduced to normal pressure (580 mm Hg, on the Hafelekar). The observations in the first three years were taken with a Steinke ionization chamber (10 atmos. CO_2), shielded with 10 cm lead from all sides. In 1936 and 1937 an additional shield of 7 cm iron was used. The latter data were reduced to 10 cm lead shielding by using a constant factor derived from the comparison of the yearly means with 10 cm Pb alone and with 10 cm Pb plus 7 cm Fe. In the table all values of the cosmic-ray intensity are given in mI (1 mI = 0.001 ion pairs/cc. sec. in air of NPT). These data are shown by the heavy curve in Fig. 1. If all these data are reduced to the same outdoor temperature (annual mean $-1°$ centigrade), using a uniform temperature coefficient of -2.4 mI (-0.9 percent) per degree centigrade, as found in the average from the monthly means of all five years, the seasonal variation is much reduced, but not completely eliminated. This can be seen from Fig. 1, where the thin line is the temperature corrected curve.

The experimental curve (cf. Fig. 1, heavy curve) shows a rather abrupt change from winter to summer while the increase from summer to late fall is more gradual. W. P. Jesse has also noticed a rather sudden change from April to May in his measurements in the stratosphere.

The amplitude of the uncorrected seasonal variation on the Hafelekar (48.4° North geomagnetic lat.) in the five year average is ± 25 mI or about ± 0.91 percent of the total intensity. The thin curve (with temperature correction) would give an amplitude of only half of this magnitude (± 0.46 percent).

These figures essentially agree very well with the results from other stations where data have

[6] J. A. Priebsch and W. Baldauf, reference 2, p. 594.

[7] B. F. J. Schonland, B. Delatitzky and J. Gaskell, Terr. Mag. **42**, 137 (1937).

been collected for sufficiently long periods (not less than one year) with Compton's model *C* cosmic-ray meters.[8, 9] In Cheltenham (Maryland) the amplitude was ±2.15 percent, in Teoloyucan (Mexico), in 2300 meters altitude it was ±0.86 percent, at Christchurch (43.5° S lat.), New Zealand and in Huancayo the amplitudes were much lower, ±0.27 and ±0.15 percent, respectively. Schonland in Capetown (South Africa), 32° geom. lat. S reported an amplitude of ±0.8 percent.

Seasonal changes were also studied on the numerous voyages of Compton and of Millikan and their co-workers on the Pacific Ocean. *It seems that at lower geomagnetic latitudes, the seasonal variations as well as the temperature effect itself become much smaller.* Millikan, Neher and Smith[10] found no seasonal effect on cosmic-ray intensity between Los Angeles (lat. 41° N) down to the Straits of Magellan (42° S) exceeding the normal fluctuations of observations. Between Los Angeles and Vancouver (B.C.), however, an increase of 2 to 3 percent was observed in winter and spring, in accordance with observations at other stations, in latitudes beyond the "knee," as discussed above. In summer and autumn no such change, exceeding 1 percent, was noticeable.

It may be mentioned that it has been shown recently[11] that the seasonal variation of cosmic radiation is also closely correlated with the corresponding regular variations of the horizontal intensity of the earth's magnetic field. In our observations in 1936 to 1937 the correlation coefficient between cosmic-ray ionization and horizontal intensity was -0.752 ± 0.126, while the regression coefficient of this effect turned out to be -0.1 percent of the cosmic-ray ionization per gamma ($1\gamma=10^{-5}$ gauss). The ratio of the relative variation of cosmic-ray ionization I to that of the horizontal force H was here $\Delta I/I : \Delta H/H = -22$. Theoretically it seems that a strong negative correlation of this magnitude cannot be explained,[12] and it is rather probable that the seasonal variations of I and H are not causally related to one another.

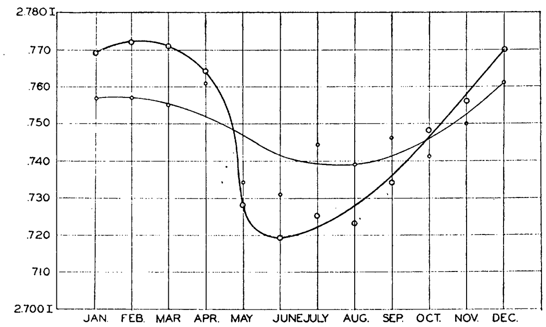

FIG. 1. Five-year mean monthly values of cosmic-ray ionization observed at 2300 m elevation, geomagnetic latitude 48° N. Heavy curve, corrected only to mean barometer. Thin curve, corrected to both mean barometer and mean temperature.

Recently M. S. Vallarta and O. Godart[13] have published the first quantitative theoretical explanation of time variations in cosmic-ray intensity. From this it seems that the solar magnetic field does not account fully for the seasonal variation with a twelve-month period, and that, although a seasonal variation with a six-month wave (maxima in March and September) is predicted by this theory, neither the amplitude nor the phase actually found is in agreement with it. Vallarta and Godart conclude: "It is thus clear that other influences are at work for the seasonal variations in addition to the direct influence of the sun's magnetic field." These influences which also should account for the observed seasonal variations in the lower latitudes are, according to the authors, possible ionospheric influences and the temperature effect. The possibility of ionospheric influences on time variations of cosmic-ray ionization has been brought up six years ago also by other authors.[3]

II. The Temperature Effect

According to Blackett,[14] the temperature coefficient is

$$\alpha\equiv-\frac{1}{I}\frac{dI}{d\theta}=-\frac{1}{L}\frac{dz}{d\theta},$$

where dz denotes the change in the mean height

[8] S. E. Forbush, Phys. Rev. **54**, 975 (1938).
[9] P. S. Gill, Phys. Rev. **55**, 429 (1939).
[10] R. A. Millikan, H. V. Neher and D. O. Smith, Rev. Mod. Phys. **11**, 167 (1939).
[11] V. F. Hess, A. Demmelmair and R. Steinmaurer, Sitz. Ber. Akad. d. Wiss, Wien **147**, 89 (1938).
[12] T. A. Johnson, Rev. Mod. Phys. **10**, 229 (1938).
[13] M. S. Vallarta and O. Godart, Rev. Mod. Phys. **11**, 180 (1939).
[14] P. M. S. Blackett, Phys. Rev. **54**, 973; Nature **142**, 992 (1938).

of the mesotron-producing layer for a temperature change $d\theta$, and dI is the corresponding change in ionization. L, is the distance traveled by the mesotron during its mean life. Using $L=32$ km, and $dz/d\theta=0.05$ to 0.064 km per degree, Blackett calculates values of α as from -0.16 to -0.20 percent, which are of the observed order of magnitude. More recent measurements[15] have indicated a much lower value for L (8.5 km), but corresponding changes in the estimated value of $dz/d\theta$ leave the calculated value of α not greatly altered. It is noteworthy that Blackett's prediction of a decreased value of α near the equator, arising from a greater value of L appropriate to the higher mean cosmic-ray energies at low latitudes, has been confirmed by the observations of Compton and his collaborators.[16]

The seasonal extremes of the 5-year average ionization at Hafelekar are 2.770 and 2.720 I, corresponding to monthly mean temperature extremes of $-9°$ and $+8°$C. We may thus calculate directly

$$\alpha=\delta I/I\delta\theta=-0.107 \text{ percent per degree,}$$

which differs only slightly from the more rigidly computed value of -0.9 percent per degree given above.

This value is somewhat less than that predicted by Blackett. Compton and Gill[16] find yet smaller values of α in the equatorial zone, which however rises to a maximum of about -0.25 percent per degree at latitudes beyond the knee of the latitude effect curve. The considerably smaller effect present in our data, taken at geomagnetic latitude 48.4° N, cannot be ascribed to the relatively high location of the observatory, since in the neighboring Inn valley, some 1700 m lower, the values of α were essentially the same (-0.11 percent per degree).[17] In light of the finding of Clay and Bruins[18] that at Amsterdam the temperature coefficient is reduced from -0.21 percent per degree to zero as the shield is increased from 12 cm to 110 cm of iron, the relatively small effect which we find may be partly ascribable to our relatively heavy shield. Also the small surface atmospheric temperature changes on the ocean should increase the numerical value of the temperature coefficient as observed by Compton and Gill. Our results are thus not inconsistent with the data of other observers.

When the top shield is removed from the ionization chamber, our earlier studies[19] have shown an entirely different kind of temperature effect, the coefficient becoming positive in the warmer months. The results for 1932 to 1939 for the temperature coefficients on the Hafelekar, (unshielded from above, 10 cm Pb on sides and bottom) are in percent per degree; winter, -0.060, spring, $+0.051$, summer, $+0.057$, autumn $+0.054$. Observations with unscreened Geiger-Müller counters in triangle arrangements made by my collaborators[20] also show the positive effect in summer and negative effect in winter. Thus it appears improbable that the positive effect found with our unshielded chamber is wholly ascribable to the variable radon content of the atmosphere.

A careful analysis of the vast observational material on which the present study is based shows that a somewhat similar seasonal variation of the temperature effect occurs likewise when the ionization chamber is fully shielded. The results of the analysis are summarized in Fig. 2 (for details, see references 2). The coefficients corresponding to each datum point were derived by the method of multiple correlation, taking I, B (barometer), and θ (outdoor temperature) as the three variables, and calculating the correlation and multiple regression coefficients for each month for the five years (except November, 1936, and April, 1937, when the data were unreliable).

It is evident that the general feature of larger coefficients in the cold season and smaller in the summer repeats itself regularly every year. The lower absolute values observed in 1936/37 are due primarily to a difference in the method of calculation. For 1932/34 the temperature coefficients were derived from the *daily* mean values

[15] B. Rossi, H. Van Norman Hilberry and J. Barton Hoag, Phys. Rev. **56**, 837 (1939).
[16] A. H. Compton and P. S. Gill, Rev. Mod. Phys. **11**, 136 (1939); P. S. Gill, Phys. Rev. **55**, 1154 (1939).
[17] R. Steinmaurer, Gerlands Beitr. z. Geophys. **45**, 148 (1935).
[18] J. Clay and E. M. Bruins, Rev. Mod. Phys. **11**, 158 (1939); Physica **6**, 628 (1939).
[19] J. Priebsch and R. Kramer, Anzeig. Wien, Akad. d. Wiss. Jan. 14, 1937.
[20] Dissertations of R. Sommer and of L. Jaeger, University of Innsbruck (unpublished), 1935 and 1936.

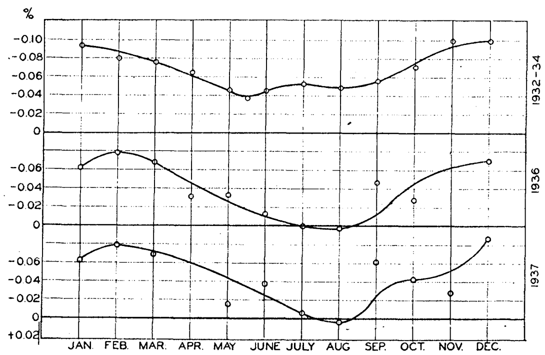

FIG. 2. Monthly values of temperature coefficient of cosmic rays. 1932–34, J. Priebsch and W. Baldauf; 1936, A. Demmelmair; 1937, F. X. Roser.

(reduced to normal pressure), while in 1936/37 the *hourly* values were used. In the latter case the data include the regular diurnal variation of intensity and temperature, both of which reach a maximum shortly after noon. This introduces a positive correlation, and reduces the numerical value of the "real" temperature effect, which is on the whole negative. As has likewise been pointed out by Barnóthy and Forró,[21] it is thus clear that a reliable absolute value of the temperature effect can only be derived from daily mean values or from values for hours when the diurnal temperature change is small. Following Priebsch and Baldauf,[2] therefore, who used the daily mean values for 1932/34, we may consider their values of α of -0.12 percent per degree in winter and -0.055 in summer to be the most reliable.

It is noteworthy that Priebsch-Baldauf and Roser find twice as great correlation between ionization and temperature in winter ($R_{i,t}=-0.044$) as in summer ($R_{i,t}=-0.024$), and at all times a much lower correlation than that between ionization and barometer, which always exceeds -0.8.

If we use the seasonal values of α just given instead of the uniform coefficient from which the thin curve of Fig. 1 was calculated, the residual seasonal changes after the temperature correction has been applied remain just as prominent as with the simpler calculation. It thus seems rather certain that part of the seasonal wave amplitude (± 0.4 percent, as in Fig. 1) is *not* caused by a temperature effect. That is, *if all ionization values are reduced to normal pressure and to annual mean temperature, there remains a marked difference between the cosmic-ray ionization values in winter and in summer; the latter being invariably lower than the former by a difference amounting to about 22 mI (0.8 percent).*

The present study nevertheless confirms previous investigations in ascribing a part of the seasonal effect to temperature changes in the atmosphere. We now have, however, additional and apparently conclusive evidence that *the temperature coefficient varies with the season by a factor of about 2.*

To account for this change in the temperature coefficient on the basis of Blackett's theory would seem to mean that the average height of the mesotron-producing layer likewise changes by a factor of 2, an assumption that would be quite inadmissable. Recently Loughridge and Gast[22] have found changes in cosmic-ray intensity associated with the so-called cold and warm fronts in the atmosphere, from which they estimate changes dz in the height of the mesotron producing layer of from 0.2 to 0.4 km. It may be hoped that such studies will eventually reveal the true nature of the temperature effect of cosmic radiation, which is mainly governed by the mass distribution in the column of air above the point of observation.

Certainly the temperature effect on cosmic-ray intensity is a much more complicated phenomenon than has hitherto been assumed, and existing theories do not account for its varied aspects.

[21] J. Barnóthy and M. Forró, Zeits. f. Physik **104**, 534 (1937).

[22] D. H. Loughridge and Paul Gast, Phys. Rev. **56**, 1169 (1939).