On the Correlation between Geomagnetic Activity and the Diurnal Variation of Cosmic Rays

By ARNE ELD SANDSTRÖM, Fysiska Institutionen, Uppsala

(Manuscript received December 9, 1954)

Abstract

The cosmic ray measurements of K.-G. MALMFORS (1949) Oct. 1947—May 1950 have been studied with regard to the effect of geomagnetic activity on the diurnal variation. By means of the same data a study was also made of the secular phase shift first noticed by ELLIOT and THAMBYAPHILLAI (1953). The time of maximum has been found to decrease with increasing values of the international K_p-index, while the amplitude itself increases. These effects were studied for the registration period as a whole as well as for short intervals. The statistical fluctuations are too big for the study of intervals shorter than half a year. The secular phase shift is the same regardless of direction. Also the phase shift accompanying geomagnetic activity is independent of the direction of measurement. This is a good proof that both shifts are due to changes in the original direction of the primaries. It is also shown, that the secular phase shift is independent of the daily geomagnetic disturbances. Apparently two effects exist, both resulting in a change of the direction of the primary cosmic ray particles.

1. Introduction

In Oct. 1947 K.-G. Malmfors started measuring the cosmic ray intensity in the Z, N, and S directions in Stockholm (magn. lat. 58°). Some of these measurements (Oct. '47—Jan. '49) have been published as a study of the daily variation (MALMFORS 1949). The counter telescope arrangement is described in the same paper. As regards the present study, the following features are of interest. The N and S directions made angles of 27° with the Z direction. The maximum angular aperture in the NS plane was roughly 50° and in the EW direction 105°. The telescopes consisted of four channels in each direction, the normal counting rate for each N and S channel being 8,000 and for each Z channel 12,000 counts an hour. The counters were arranged for twofold coincidences. In the present paper Malmfors' measurements for the period Oct. '47 to May '50 are treated with regard to the influence of geomagnetic activity. SEKIDO and KODAMA (1952) reported the existence of such an effect.

The counting rate cited above is too low for a detailed day by day study. Accordingly, we are obliged to do the sums of the bihourly values for sequences of days having approximately the same degree of geomagnetic activity. However, if a phase shift is superimposed upon the expected effect, the latter may possibly be partly obliterated. As regards the time of maximum amplitude ELLIOT and THAMBYAPHILLAI (1953) have shown that such a phase shift really exists.

2. The Secular Phase Shift

The diagram of ELLIOT and THAMBYAPHILLAI (1953) includes one point from MALMFORS' measurements. As it ought to be especially

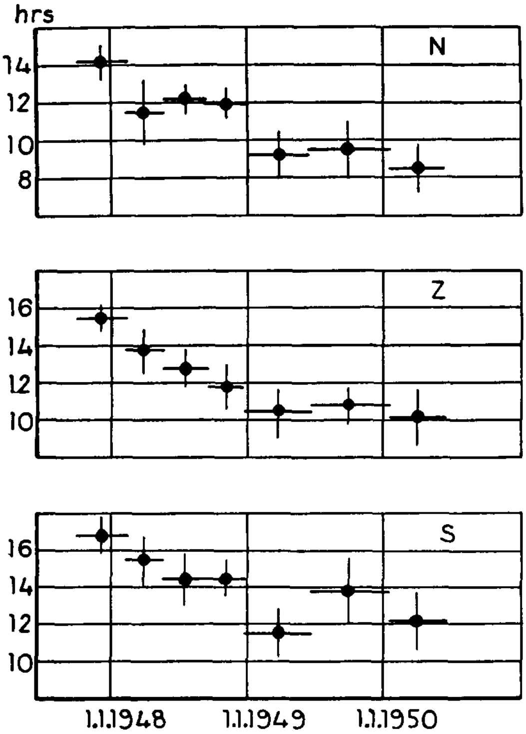

Fig. 1. The phase shift from Oct. '47 to May '50. The length of the vertical lines through the points of measurements represent the statistical fluctuations. The horisontal lines indicate the intervals within which the sums of the bihourly values were done.

interesting to follow the changes with one and the same set of telescopes, a similar diagram has been drawn using Malmfors' original "100"-day periods supplemented with three further periods (Fig. 1).

From Oct. '47 to May '50 there is a marked decrease regarding the time of maximum amplitude. Within the statistical fluctuations the shift is the same in all the three directions. From the diagrams (Fig. 1) we deduce an average continuous shift of 2 hours a year. Accordingly, if the available cosmic ray data are arranged in half year intervals, the amplitude vector will move through 1/24 of the harmonic dial during each interval. As this is a comparatively small part of a whole period, the sum of the first harmonics will certainly mirror the true features of the components. However, when the days are classified according to geomagnetic activity, days belonging to one and the same class never constitute a continuous sequence where half a year or longer intervals are concerned. Accordingly the resulting harmonic might still be influenced by the distribution of the days. Especially as regards such a long interval as Oct. '47—May '50 we recognize the possibility of a considerable influence from such sources, at least as far as classes containing a small number of days are concerned.

3. Classes of Geomagnetic Activity

The planetary index K_p was taken as a measure of the daily geomagnetic activity (Bartels 1949). This international index is tabulated for every three hours a day in tables published by the international Union of Geodesy and Geophysics (Howe and Weisman 1949, Bartels and Veldkamp 1950, 1951). The days were classified according to the highest K_p-number for any of their 3-hour periods (Table 1).

For the whole period Oct. '47—May '50 there are only 26 days in class I and 9 in class V. Accordingly the statistical fluctuations are very great, especially as regards the latter case. Some doubts may arise concerning our mode of classifying the days according to their maximum K_p-index, even if most of their 3-hour periods have low indices. It seems quite natural to use the daily sums of the

Class	K_p-index maximum value	Number of days														
		Oct. '47—March '48			Apr. '48—Sept. '48			Oct. '48—March '49			Apr. '49—May '50			Oct. '47—May '50		
		N	Z	S	N	Z	S	N	Z	S	N	Z	S	N	Z	S
I	1 +	6	6	6	4	4	4	6	6	6	9	7	10	25	23	26
II	3 +	71	71	71	72	71	72	50	49	50	133	78	113	326	269	306
III	5 +	65	67	67	68	68	68	78	78	78	76	72	75	287	285	288
IV	7 +	7	7	7	9	9	9	19	19	10	17	15	17	52	50	52
V	9 +													9	9	9

K_p-indices instead. However, as yet our knowledge about the interchange between cosmic rays and geomagnetic activity is insufficient for a decision between these two types of classification. A survey also reveals that days with one or a few K_p-indices above the selected limit usually have most of their other K_p-indices just below the same limit. Accordingly, with the present rate of accuracy this question is undoubtly of slight significance. As regards all the five classes of Table 1 the average K_p-index is approximately 2/3 of the maximum value.

4. The Statistical Fluctuations

The precision of the two harmonic coefficients p and q is limited mainly by the statistical fluctuations. The corresponding influence on the value of the amplitude and the time of maximum can be calculated directly from the bihourly values. The fluctuations of the maximum amplitude are evidently limited by

$$\pm 100 \cdot \frac{|p \Delta p| + |q \Delta q|}{\sqrt{p^2 + q^2}}$$

The numerical factor indicates that p and q are expressed in per cent of the average cosmic ray intensity. The statistical fluctuations affect p and q by the same amount. Let N_i be the number of impulses during each individual bihourly period and N the average. Then we have the relations

$$\Delta p = \frac{1}{6} \cdot \sqrt{\sum_{i=0}^{2\pi} \left[\Delta \frac{N_i - N}{N} \right]^2 \sin^2 \varepsilon_i}$$

$$\Delta \frac{N_i - N}{N} = 2\sqrt{N}$$

Accordingly, the value of the maximum amplitude is statistically limited by

$$\pm 100 \cdot \frac{\sqrt{6}}{3} \frac{|p| + |q|}{\sqrt{p^2 + q^2}} \cdot \frac{1}{\sqrt{N}}$$

If in the harmonic dials a circle with a radius as given by this expression is drawn with the point p/q for a centre, we also get a measure as to the influence of the statistical fluctuations on the time of maximum.

The telescopes were arranged for two-fold coincidences. Accordingly, the influence of spurious counts cannot be neglected. The statistical fluctuations calculated from the total number of counts will be too low by a factor depending on the ratio of spurious counts. The increment is far from constant, as this ratio is a function of the background and therefore also of the age of the counter. However, in the present case the increase of the statistical fluctuations does not exceed 20 per cent. This estimate has not been included in the circles indicating the statistical uncertainty.

5. The Influence of Trends

The daily averages show a systematic variation with a period of one year, but the trend is not sufficiently large to affect the daily variation. The 27-day period of the daily cosmic ray intensity is more important, as are the less regular changes covering one or two days. A negative trend causes the daily maximum to appear too early, while a positive trend displaces it towards the other direction. Most important is that the amplitude is diminished by all negative trends. A large one tends to obliterate the daily variation.

However, even when the days are divided into classes according to geomagnetic activity, days with positive and negative trends will be comparatively evenly distributed. The number of days with a negative trend does not seem to be a function of the geomagnetic activity.

For a closer study the days of classes II and III during Oct. '47—March '48 were divided into two groups according to the sign of the trend. As expected, the maximum appears earlier in the day for those having a negative trend than for those having a positive trend, but the difference in time is less than the range of statistical fluctuations. Accordingly we conclude that, at least in the present case, the distribution of days between positive and negative trends is sufficiently random to eliminate the displacement of the time of maximum. As the number of days has to be sufficiently large to fulfill the condition of random distribution, the influence of the trend will be most apparent as regards days with very low or very high geomagnetic activity, i.e. classes I and V. However, in the latter case the amplitude is fairly great and the trend can therefore be correspondingly large without any serious effects.

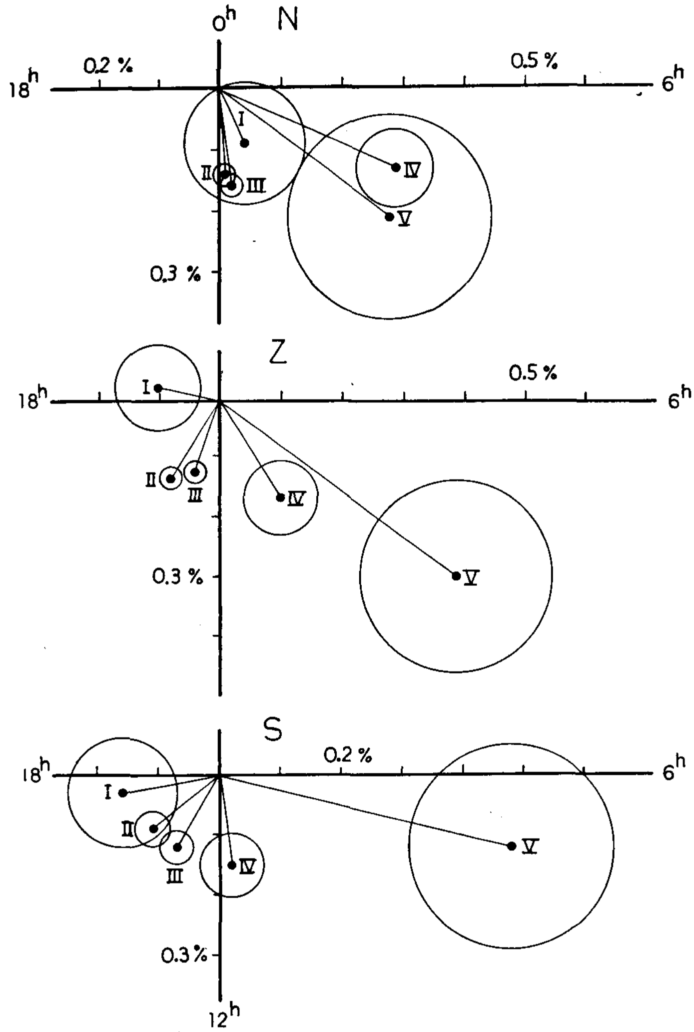

Fig. 2. Harmonic dials for the N, Z, and S directions showing the effect of geomagnetic activity. The circles indicate the magnitude of the statistical fluctuations.

6. Oct. '47 – May '50

Although the slow phase shift certainly influences the average over a long period of the time of maximum amplitude, the accompanying relative decrease of the statistical fluctuations is a sufficient reason for calculating the sums of the bihourly values for such a long interval as Oct. '47 to May '50. Dividing the days into the classes I to V (Table I) we get the results represented by the harmonic dials of Fig. 2. There cannot be any doubt whatsoever that geomagnetic activity affects the time of maximum amplitude as well as the amplitude itself. This is fully displayed by the Z and S directions. The N direction reveals to some extent different features, the effect being so small as not to surpass the limited resolution.

As regards the Z direction the maximum shift is slightly less in the present case than in that reported by SEKIDO and KODAMA (1952). These authors found a 12

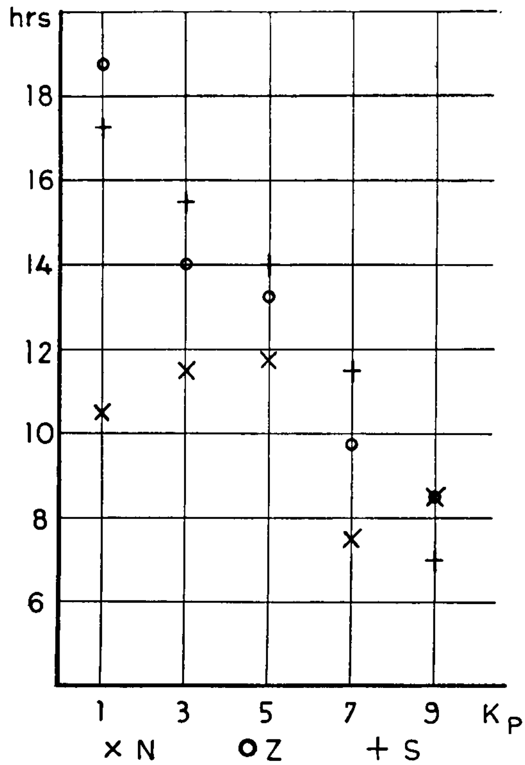

Fig. 3. The time of maximum amplitude as a function of geomagnetic activity.

hours' difference where we have 10 only. With due regard for the statistical fluctuations this discrepancy is insignificant. Below we shall discuss at some length whether the phase shift is really as large as indicated even by the lower of these two values.

In Fig. 3 the time of maximum amplitude is given as a function of geomagnetic activity. The Z and S directions display the same average shift. As regards the N direction, the difference as compared to the other two directions is more apparent in this diagram than in the harmonic dials. However, we must always remember the unreliability due to the statistical fluctuations. As has been mentioned the ultimate limits of errors may be twice as great (compare Fig. 7).

Apparently the amplitude shifts in the same way regardless of direction. Fig. 4 shows that the points representing the Z, N, and S directions can be regarded as distributed along one and the same curve.

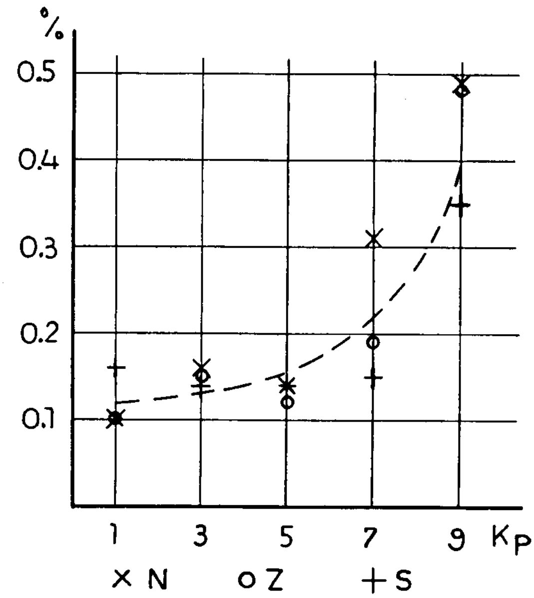

Fig. 4. The amplitude as a function of geomagnetic activity.

7. Short intervals

The measurements from Oct. '47 to May '50 have been divided into three six month intervals and one interval of 14 months. The latter had to be added because from April '49 until May '50 the telescope set did not work as well as before. Although a lot of valuable data were acquired, the registrations were broken off too frequently by several of the counters' becoming unreliable at one and the same time.

During each interval class V was represented by too few days to justify its being plotted in the harmonic dials. Even as regards classes I and IV the statistical fluctuations are so great as to make it impossible to resolve them from the neighbouring classes. Nevertheless we are able to decide that Fig. 5 displays the same general tendency as do the harmonic dials for Oct. '47—May '50. The small separation between classes II and III is as apparent in these diagrams as in those of Fig. 2. Considering the limits of errors, the amplitudes appear to follow the same rule as do the averages for Oct. '47 –May '50.

An attempt was also made to study the influence of geomagnetic activity during calendar months. However, from Fig. 5 it already

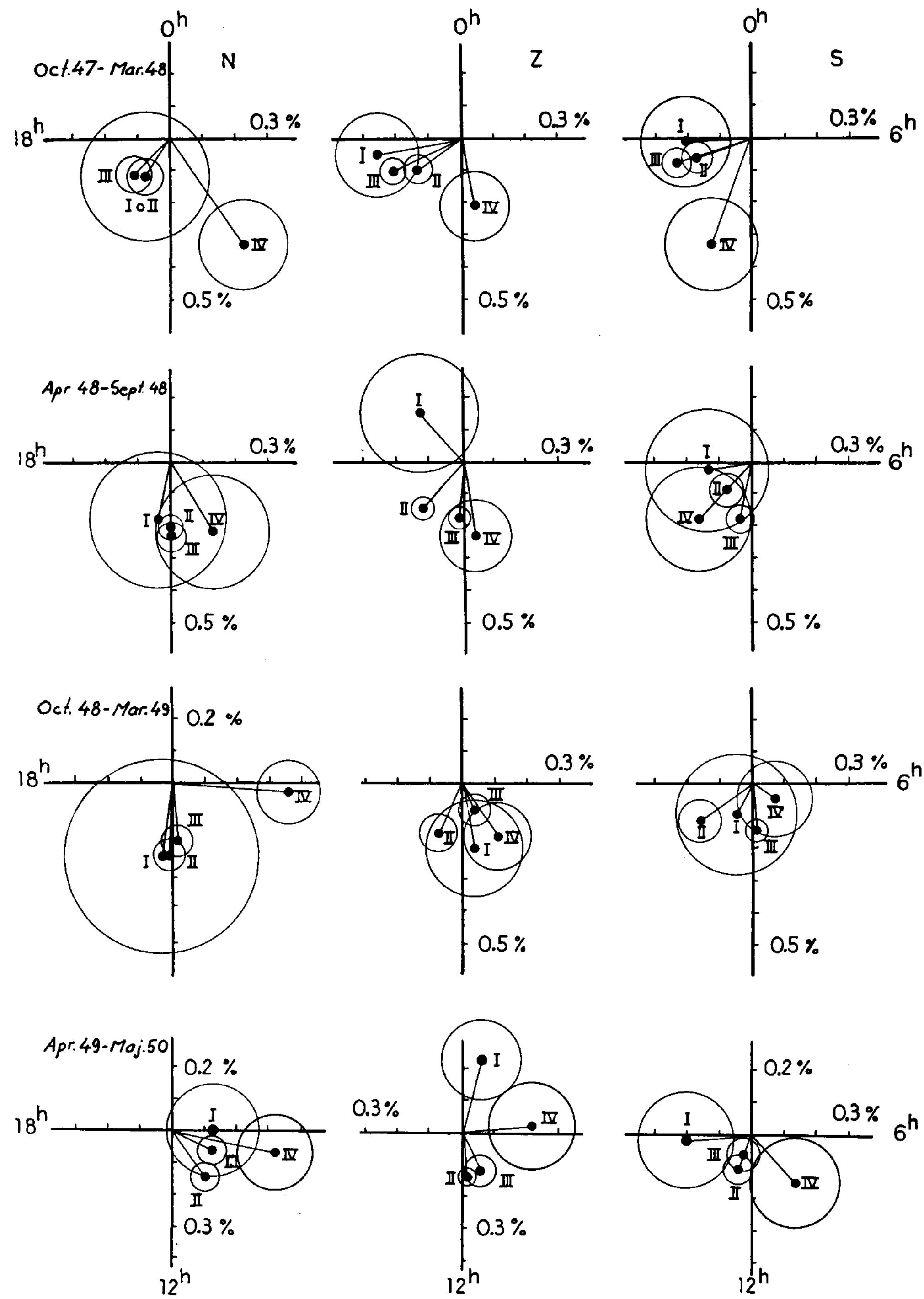

Fig. 5. Harmonic dials for the half year intervals.

appears that with a counting rate as low as in the present case half a year is probably the shortest possible interval.

According to BRUNBERG and DATTNER (1954) a geomagnetic storm probably affects the cosmic rays for a time after the end of the storm itself. As the time of maximum is a function of the geomagnetic activity, it ought to be possible to study some of the variations by doing the sums of the bihourly values for a 5—7 day interval before the period of increased geomagnetic activity, the days during the increased activity and a sequence of 5—7 day intervals during the period of decreasing activity. For this purpose we selected five periods with high geomagnetic activity preceding fairly long intervals of quiet days.

As can be gathered from the two examples in Fig. 6, the accuracy is far too low for any reliable conclusions to be drawn. In the second example the resolution is sufficiently high to reveal the usual tendency of the time of maximum to decrease with increasing geomagnetic activity. There are also some indications that the maximum appears early in the day during the first part of decreasing activity.

Mostly, however, the harmonic dials show the same features as the first example of Fig. 6, the statistical fluctuations being great enough to account for the whole shift. The counting rate ought to be so high that it becomes possible to follow the changes day by day. To be able to resolve time differences of the order of one hour, the counting rate has to be at least $5 \cdot 10^6$ counts/hour.

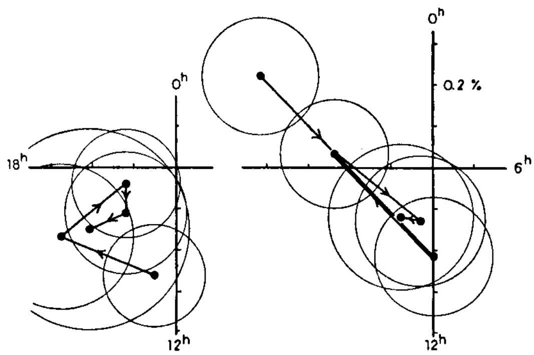

Fig. 6. Harmonic dials for the Z direction during two intervals of varying geomagnetic activity. The points represent the following intervals in order: To the left: Oct. 1—7, 10—15, 18—24, 25—30, and Oct. 31—Nov. 6, 1947. To the right: March 5—11, 12—15, 16—22, 23—29, and March 30—Apr. 5, 1948.

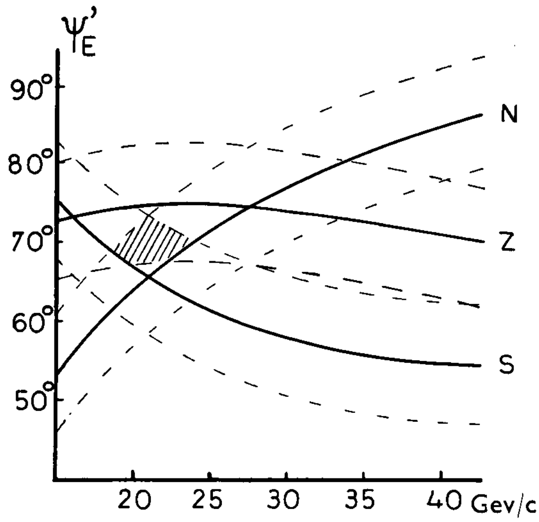

Fig. 7. The direction of anisotropy in the equatorial plane as a function of momentum according to Brunberg and Dattner (1954). The dotted lines indicate the statistical fluctuations. Ψ'_E is the sum of local time and the deflection of the particles due to the magnetic field of the earth. Geomagn. lat. 58°.

8. The Energy of the Primaries

BRUNBERG (1953) has made an experimental study of orbits of charged particles in the earth's magnetic field. As a result the true direction of the primary particles can be calculated from the directions and geometry of the counter telescopes. As a further step BRUNBERG (1953) and BRUNBERG and DATTNER (1954) calculated the east—west deflection as a function of the momentum of the primaries. The curves corresponding to the N, Z, and S directions ought to pass through one and the same point corresponding to the average energy of the primaries. Their diagram is reproduced in Fig. 7 with the addition of the statistical fluctuations. With due regard for the latter, Brunberg and Dattner found the average momentum of the primaries to be 20 GeV/c.

It is of special interest to observe how the diagram of Brunberg and Dattner is affected by a phase shift of the diurnal variation. If the shift is the same as regards all the three directions, the corresponding curves will move up or down in the diagram, the constant momentum coordinate of the intersection point indicating that the average momentum of the primaries is unaffected. Then the shift certainly originates from changes in the directions of the primaries.

On the contrary, if the shifts of the N, Z, and S directions differ, the intersection point will be displaced as regards the momentum coordinate. Accordingly there is a change of the energy distribution either as regards all the three directions or as regards one or two of them.

9. Discussion

Fig. 1 reveals the secular phase shift of the diurnal variation as being the same regardless of direction. Accordingly, from what has been said above, the energy distribution does not vary but the whole shift is due to a directional change of the primaries. This is in full agreement with the theory of ALFVÉN (1954), which tells us that the phase shift is due to the interplay between two 24 hours harmonics having a phase difference of 6 hours. The majority of cosmic ray particles is bound to the rotation of the sun. They overtake the earth in its orbit, producing a maximum at 18^h. In addition there is a direct radiation of particles from the sun. Propagated in a radial direction, these particles produce a maximum at 12^h. An early maximum indicates that the radial stream of particles dominates over that overtaking the earth in its orbit. Both streams of particles are deflected by the earth's magnetic field with a phase shift as the result. By means of the curves published by BRUNBERG (1953) the original directions of the primaries can be determined from their ultimate directions as observed at the surface of the earth. Unless there is a change of energy distribution, the shift should be the same regardless of the direction of the telescopes. As has been pointed out, this is the case as regards the measurements in Stockholm 1947—1950.

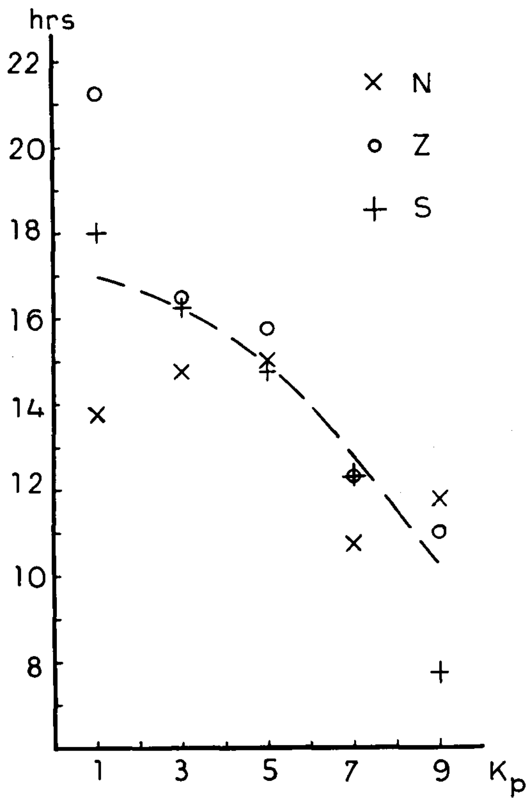

Fig. 8. The time of maximum as a function of geomagnetic activity after correcting, according to Brunberg, for the deviation of the primary particles in the magnetic field of the earth.

Turning to the geomagnetic effects our discussion meets with difficulties mostly due to the comparatively low accuracy of the telescope measurements. As already mentioned, the N direction differs in a marked manner from the other two directions (Fig. 3). If this difference were real, the N direction would display a change of energy distribution accompanying the increase of geomagnetic activity, while the other two directions would not. However, Fig. 4 indicates that inside the limits of errors the amplitude shift is the same in all the three directions. This makes it more difficult to understand why the N direction differs as regards the time of maximum. Regarding classes III to V, only, we find that the shift can be considered as the same regardless of direction.

According to BRUNBERG (1953) and BRUNBERG and DATTNER (1954) we ought to find the same time of maximum of each one of the three telescope directions, if we correct for the deviation by the magnetic field of the earth. In Fig. 8 this correction has been applied by adding $3^1/_4$ hours to the N-, $2^1/_2$ hours to the Z-, and $^3/_4$ hour to the S-direction (compare Fig. 3). In each case the points representing classes II, III, and IV fall close together. With due regard for the low accuracy, the points of classes I and V are also inside the limits of errors. The low accuracy also explains why the three directions become mixed up as regards the time of maximum on very quiet and very disturbed days as compared to those of average geomagnetic activity.

Studying the harmonic dials in Fig. 5 we find that as regards the Z and S directions during days belonging to class I the maximum nearly coincides with that of classes II and III in five cases out of eight. As regards the Z direction we also note that one of the harmonic dials (Apr. '48—Sept. '48) disagrees thoroughly with all the others. This might cause the disagreement already remarked upon.

The general impression from the harmonic dials of Fig. 5 is that the phase shift is very small between classes I, II, and III. Then, as a function of the K_p-index, the time of maximum ought to follow the dotted line in Fig. 8.

From the discussion above the author feels justified in concluding that the observed differences between the N direction and the other two directions is due to insufficient accuracy only. Concerning classes II (maximum K_p-index 3^+), III (maximum K_p-index 5^+), IV (maximum K_p-index 7^+), and V (maximum K_p-index 9^+), the shift is undoubtedly the same regardless of the direction of the telescopes. As regards the very quiet days of class I (maximum K_p-index 1^+) there still is a slight possibility of a difference in phase shift. This would indicate that during geomagnetically quiet days the energy distribution of the primaries is another in the N direction than in the other two directions, which could be due to the magnetic field of the earth only. From Brunberg's curves we gather that the angle Φ_N is roughly 25° for the N direction and 33° and 35° for the Z and S directions respectively. This is too small a difference in angle to result in such an effect, especially as the geometry of the telescopes was such as to result in a considerable overlapping of the N and Z directions.

We will not enter into further discussion here, as we feel that more measurements are necessary for a thorough understanding of these problems. Also, as far as this kind of measurements is concerned, the investigations should be made with telescopes having comparatively small and well defined apertures.

The dependence of the diurnal variation on the geomagnetic activity raises an interesting point concerning the secular phase shift (Fig. 1). It can be argued that this shift could be due to an increasing frequency of geomagnetic disturbances. If this were true, however, there should not be any or only a small shift in each separate geomagnetic class of days. We find from Fig. 5 that the low resolution leaves us classes II and III only for a study. For better judgement we reproduce the corresponding points in the harmonic dials of Fig. 9.

Although the statistical fluctuations are comparatively great, most of the dials in Fig. 9 put the existence of a secular phase shift even for days with equal geomagnetic activity beyond any doubt. Advancing one step further we correct for the deviation of the primaries in the magnetic field of the earth and plot the points in the diagram of Fig. 10. As in the case illustrated in Fig. 8 we ought to find the same time of maximum regardless of direction. Therefore we are justified in reckoning with the averages of the three values for each date. The existence of a phase shift is quite apparent in both the illustrated cases. It has an average value, indicated by the dotted lines, of 2 hours a year, which is the same as the phase shift for all days regardless of geomagnetic conditions (Fig. 1).

As a result of this part of our discussion we find that the secular phase shift is independent of the geomagnetic activity characterized by the K_p-index. From this it does not follow that it is independent of all geomagnetic effects, as the K_p-index is related only to the daily disturbances, the secular changes being eliminated.

10. Conclusions

1. The secular phase shift of the diurnal variation as found by Elliot and Thambyapillai is the same regardless of the direction of the telescopes. Accordingly this phase shift depends only on the initial direction of the primaries.

2. The secular phase shift is independent of the daily geomagnetic disturbances as characterized by the K_p-index.

3. The time of maximum amplitude decreases with increasing geomagnetic activity as already found by Sekido and Kodama. Probably, the decrease is smaller than reported by them.

4. The amplitude of the first harmonic increases with the geomagnetic activity.

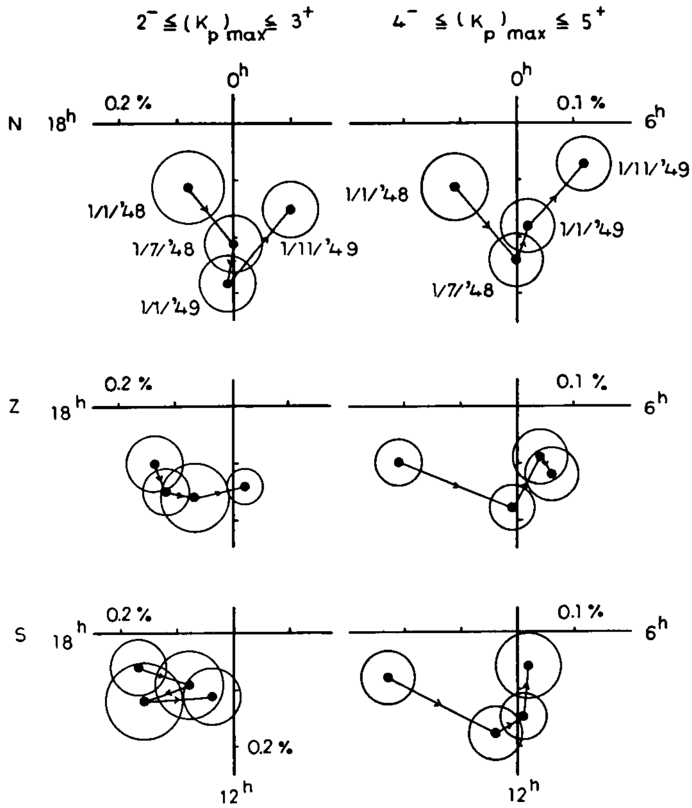

Fig. 9. Harmonic dials for the N, Z, and S directions showing the secular shift for days of equal geomagnetic activity. The dates ascribed to the four consecutive points are the centres of the corresponding intervals as given in Table 1 and Fig. 5.

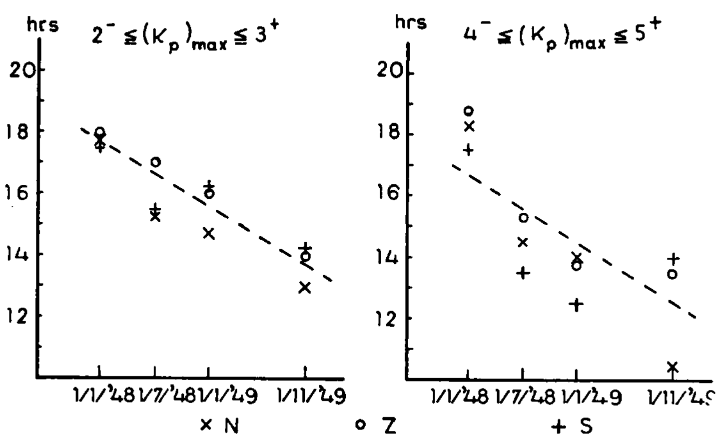

Fig. 10. The secular phase shift for days with equal geomagnetic activity. Corrections have been applied for the influence of the earth's magnetic field. The dates ascribed to the four consecutive points are the centres of the corresponding intervals as given in Table 1 and Fig. 5.

5. When $K_p \geqq 3^+$ the phase shift is certainly independent of the direction of the telescopes, thus indicating a change of the initial direction of the primaries. A discussion shows that this is probably also the case for $K_p < 3^+$.

6. The dependence of the time of maximum on the geomagnetic activity is apparent even as regards averages calculated over periods with an appreciable secular phase shift.

7. Comparing 1, 2, and 5 we conclude that two separate effects exist, both resulting in a change of the initial direction of the primary cosmic ray particles.

11. Acknowledgements

Cosmic ray work in Sweden is being sponsored by the Swedish Natural Science Research Council. The present paper is part of the work carried out under its auspices and directed by its Committee for Cosmic Ray Studies. The author thanks his fellow-members on this comittee for encouragement and discussions, especially Dr K.-G. Malmfors, who made all his measurements available for the present study.

The author also wishes to thank Miss Ulla Björkegren, who made all the numerical calculations.

REFERENCES

ALFVÉN, H., 1954: On the Origin of Cosmic Radiation. *Tellus.* **6**, p. 232.

BARTELS, J., 1949: The standardized index, K_s, and the planetary index, K_p. *International Union of Geodesy and Geophysics*, Association of Terrestrial Magnetism and Electricity. Bulletin No. 12 b, p. 97.

— and VELDKAMP, J., 1950: Geomagnetic Indices, *K* and *C*, 1949. *International Union of Geodesy and Geophysics. Association of Terrestrial Magnetism and Electricity.* Bulletin No. 12 c, p. 102—103.

— 1951: Geomagnetic Indices, *K* and *C*, 1950. *International Union of Geodesy and Geophysics. Association of Terrestrial Magnetism and Electricity.* Bulletin No. 12 e, p. 104.

BRUNBERG, E. Å., 1953: Experimental Determination of Electron Orbits in the Field of a Magnetic Dipole. *Tellus.* **5**, p. 135.

— 1953: On the Anisotropy of the Primary Intensity Time Variations. Recueil des Travaux de l'Observatoire du Pic-du-Midi. Série Rayons Cosmique No 1. Congrès International sur le Rayonnement Cosmique 1953. Session annexe sur les variations du rayonnement cosmique.

— and DATTNER, A., 1954: On the Interpretation of the Diurnal Variation of Cosmic Rays. *Tellus.* **6**, p. 73.

ELLIOT, H. and THAMBYAPHILLAI, T., 1953: World-wide changes in the phase of the cosmic-ray solar daily variation. *Nature*, May 23.

HOWE, H. H., and WEISMAN, E. K., 1949: Geomagnetic Indices, *K* and *C*, 1948. *International Union of Geodesy and Geophysics. Association of Terrestrial Magnetism and Electricity.* Bulletin No. 12 b, p. 118—120.

MALMFORS, K. G., 1949: Recordings of Cosmic Radiation. *Tellus.* **1**, p. 54.

SEKIDO, Y., and KODAMA, M., 1952: Diurnal variation of vertical cosmic rays. *Rep. of Ionosph. Research in Japan.* Vol. VI No. 2.