Direction of the cosmic ray anisotropy

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ABSTRACT

Inclined meson telescopes at Uppsala, Kiruna, and Murchison Bay have been employed to determine the direction of the C.R. diurnal anisotropy. The six mean asymptotic directions are distributed between approximately 15° N and 80° N. It is being shown that the flow of excess particles responsible for the anisotropy is parallel to the orbital plane of the earth. All atmospheric effects have been considered as well as the partial smoothing out of the diurnal variation through the longitudinal distribution of the asymptotic directions. Inside the limits of error the yearly mean amplitudes fit a linear function of the cosine of the angle between the equatorial plane and the mean asymptotic direction. The direction of the anisotropy makes an angle of approximately 90° with the earth–sun line, the flow of excess particles overtaking the earth.

Introduction

The solar diurnal variation of C.R. intensity is usually assumed to be due to the rotation of the earth in a cloud of particles. The velocities of the latter should be randomly distributed with an additional component in one direction, thus constituting a kind of particle wind. DORMAN (1957) has remarked that the anisotropy could be explained as due to an excess flow of particles from a source rotating in an orbit around the sun. With a particle wind approximately parallel to the orbital plane of the earth, the amplitude of the diurnal variation should have a maximum for primary particles having asymptotic directions approximately parallel to the equatorial plane.

The terrella experiments by Brunberg (BRUNBERG, 1953; BRUNBERG and DATTNER, 1953; BRUNBERG, 1956) revealed that the axis of an east-pointing telescope at Uppsala could be expected to correspond to the arrival direction of primaries having a mean asymptotic direction approximately parallel to the equatorial plane while a west-pointing telescope at Murchison Bay in the Arctic would record primaries with asymptotic directions making comparatively small angles with the earth's axis of rotation. The gap between the two extreme directions could be covered by a west-pointing telescope in Uppsala, an east-pointing in Murchison Bay, and north- and south-pointing telescopes in Kiruna (SANDSTRÖM 1955). The positioning of the telescopes and the selection of directions were founded on the assumption that the effective rigidity of the primaries can be assumed to be 25 GeV/c (BRUNBERG and DATTNER, 1954).[1]

Experimental details

The geographic coordinates of the three C.R. stations are: Uppsala 59.9° N, 17.9° E, Kiruna 67.8° N, 20.4° E, and Murchison Bay 18.3° E, 80.1° N. All the three stations are to be regarded as sea level stations, the altitude of that at Kiruna being only 390 m. The geometry of the directional telescopes is fully understood from Fig. 1. 10 out of the 14 trays belong to two channels, one for each direction. Each telescope set serves two directions with four channels in each direction. The full opening angle is 45°. The zenith angles of the telescope axes are 32°.

There is a separate quenching univibrator for each one of the 16 counters in each tray. It is

[1] The experiment was planned and supervised by A. E. Sandström. E. Dyring was in charge of the Murchison Bay station during one year. He has also attended to the statistical part of the work. S. Lindgren has attended to the atmospheric effects. As to the advanced treatment and discussions, the authors claim equal shares.

possible to adjust the high voltage for each counter individually. The trays have an effective surface of 60×60 cm^2.

In August 1957 the counting rates were 14,000 c/hr for each channel at Uppsala and Murchison Bay and 15,000 c/hr at Kiruna.

As no aerological data are available for Kiruna and it is impossible to make a proper correction for variations in the upper atmosphere from only two balloon ascents a day, the bihourly values have been corrected only for variations in atmospheric pressure. The correction coefficients were calculated from the data collected at the three stations. Their values are: for the inclined telescopes at Uppsala and Murchison Bay -0.20 per cent per mb and for those at Kiruna -0.23 per cent per mb.

Corrections for decay and temperature effects were added to the yearly means. This is being discussed on p. 25–26.

The harmonic analysis comprises the first and second harmonics. A linear trend correction was employed.

The standard errors are calculated from the residuals of the points of measurement obtained by fitting the sum of the first and second harmonics (DYRING and ROSÉN, 1961).

It is our opinion that the standard error from the residuals should be employed for the calculations of significances rather than the standard error deduced solely from an assumed Poisson distribution of pulses.

If conditions were ideal, the standard error calculated from the residuals should be identical with that calculated from the Poisson distribution. Usually it is bigger.

There is one important reason why errors calculated from the residuals should be preferred before those calculated from the Poisson distribution: they cover additional random fluctuations also. For instance, a special study of data from the inclined telescopes as well as the standard cubes shows that the standard error from the Poisson distribution leads to an underestimate (DYRING 1962). Because of the absence of filters in the inclined telescopes, a part of these additional fluctuations might be due to shower electrons. According to a rough calculation the contribution to the background by such electrons will be of the order of magnitude of one per cent of the normal counting rate. The additional random fluctuations are more important. However, the ratio between the standard error from the residuals and that calculated from the Poisson distribution is of the same order of magnitude for the inclined telescopes as for the cubical telescopes with filter of 10 cm lead equivalent (DYRING, 1962). This can be regarded as a proof that the absence of filters in the former does not affect the accuracy.

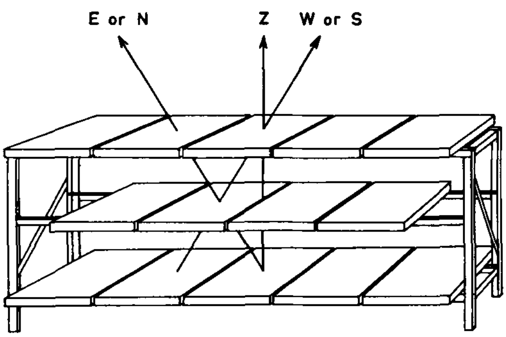

Fig. 1. The geometry of the directional meson counter telescopes.

Selection of periods

As a plausible hypothesis we will assume that the anisotropy has a fixed direction relative to the orbital plane of the earth. Then, due to the inclination of the earth's axis of rotation, there will be a seasonal variation of its direction relative to the equatorial plane. The yearly mean of the latter will be equal to its direction relative to the orbital plane of the earth. Thus yearly means ought to be employed for the comparison.

Starting from Alfvén's theory of the origin of cosmic rays (ALFVÉN, 1954), DATTNER and VENKATESAN (1959) list a number of components of the C.R. anisotropy. Some of these components are independent of the origin of cosmic rays. Most of them have one feature in common, i.e. they vary considerably during the year, affecting both phase and amplitude of the diurnal variation. To all these periodic variations can be added the universal time vector proposed by PARSONS (1960) to explain the difference in phase and amplitude of the nucleon component observed at various C.R. stations. It is still obscure what a kind of intensity variation is represented by this vector and if it is present also in the meson component.

One of the characteristics of most of the components listed by Dattner and Venkatesan

TABLE 1. *The Number of Identical Days in the 12-monthly Periods.*

Symbols: E_U, East-pointing meson telescopes in Uppsala. W_U, West-pointing meson telescopes in Uppsala. N_K, North-pointing meson telescopes in Kiruna. S_K, South-pointing meson telescopes in Kiruna. E_{MB}, East pointing meson telescopes in Murchison Bay. W_{MB}, West-pointing meson telescopes in Murchison Bay.

	A	B	C	D	E	F
Period	E_U, W_{MB}	E_U, N_K, W_{MB}	W_U, S_K, E_{MB}	E_U, W_U, E_{MB}, W_{MB}	E_U, W_U, N_K, S_K, E_{MB}, W_{MB}	E_U, W_U, N_K, S_K
I Sep. 1, 1957–Aug. 31, 1958	307	278	276	298	261	
II Calendar year 1958	312	281	284	301	268	
III May 1, 1958–April 30, 1959	317	276	279	307	256	
IV Sep. 1, 1958–Aug. 31, 1959						260
V Calendar year 1959						263
VI May 1, 1959–April 30, 1960						277
VII Sep. 1, 1959–Aug. 31, 1960						308
VIII Calendar year 1960						306

as well as of Parsons' UT vector, is that to all practical purposes they disappear in the yearly mean of the diurnal variation. Accordingly, regardless of the existence or non existence of these components, the yearly mean offers the best way of studying the main component of the diurnal variation.

The records from Murchison Bay cover the period from Sep. 1, 1957 to April 30, 1959. To make use of the complete set of records, three 12-monthly periods can be selected starting on Sep. 1, 1957, Jan. 1, 1958, and May 1, 1958 respectively. Although partly overlapping, these 12-monthly periods are valuable when judging the accuracy of the experiment.

As single days sometimes display a daily variation differing from the normal, it is advisable to employ identical days for the 12-monthly means. Thus, days with registration failures in one place or direction have to be excluded from the records. To limit the number of exclusions interpolations have been made for odd hours and single bihourly periods. Naturally, the number of excluded days will increase with the number of asymptotic directions to be compared. To ascertain how much a variation in the exclusion of days might affect the results, the directions have been divided into groups as shown in Table 1. The Kiruna records have suffered from comparatively frequent failures of the main power supply. This explains the low number of identical days in groups including the two Kiruna directions.

Despite the possible existence of variable components, short periods still furnish information of value for the present study. Being less artificial, sun rotation periods have been preferred to calendar months. It ought to be observed that, in this case, identical days have not been selected. This would have involved additional work not justified by the purpose. Days with prominent Forbush decreases are excluded.

The 12-monthly means

The results from the periods with identical days are presented in the clock diagrams in Figs. 2 to 4. These diagrams correspond exactly to the periods and directions of observation listed in Table 1. For convenience, in the text as well as in the figures, the directions of observation are represented by the symbols listed in the head of this table.

The separate comparison between W_{MB} and E_U is the most favourable one as concerns the number of identical days. Next to this comes the comparison between E_U, W_U, E_{MB}, and W_{MB} (Table 1). Especially groups B and C (Fig. 2) enable us to judge how the results will be affected when as many days have to be discarded as in the comparison of all the six directions (Fig. 3 E). The displacements are obviously of the same order of magnitude as the standard errors.

The display of vectors in Figs. 2 to 4 reveals that E_U has the biggest amplitude and that the yearly mean amplitude of W_{MB} is practically non existent (SANDSTRÖM, DYRING, LINDGREN, 1960). As expected the other four directions appear to cover the gap between the two

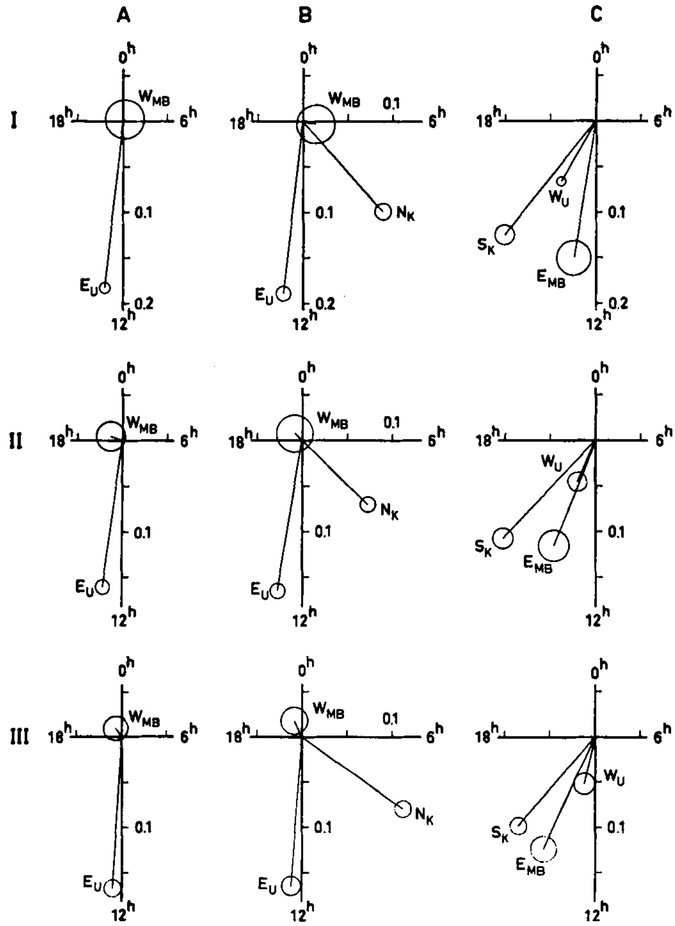

Fig. 2. Clock diagrams for the 12-monthly periods with identical days. For explanation cf. Table 1. I. Sep. 1, 1957 to Aug. 31, 1958. II. Calendar year 1958. III. May 1, 1958 to April 30, 1959.

extremes. It has to be remembered that the clock diagrams are based on values corrected only for atmospheric pressure. The introduction of corrections for temperature and decay affects the phases as well as the amplitudes (Figs. 10 and 11).

The clock diagrams in Fig. 3 E reveal a considerable phase difference between N_K and S_K. This difference varies only slightly during the period Sep. 1, 1957 to April 30, 1959. After the end of this period the phases of N_K and S_K changed in such a way as to diminish the difference (Fig. 4).

It is to be deplored that the registrations at Murchison Bay had to be discontinued. The available records refer to a period of maximum solar activity. For many reasons it would have been better to perform the experiment during a period of low solar activity. The absence, after Apr. 30, 1959, of any records of W_{MB} is bad but E_U, W_U, N_K, and S_K are still being recorded. Fig. 4 contains the clock diagrams for the calendar years 1959 and 1960 (column F, Table 1).

It is most important that during all the five 12-monthly periods, from which the clock diagrams in Fig. 4 are selected, the amplitude of E_U is much bigger than that of W_U. Although the amplitudes of N_K and S_K have shifted, both maintain an intermediate position between those of E_U and W_U.

According to BRUNBERG (1956) the asymptotic directions are referred to geographical coordinates through the two angles ϕ and ψ. ϕ

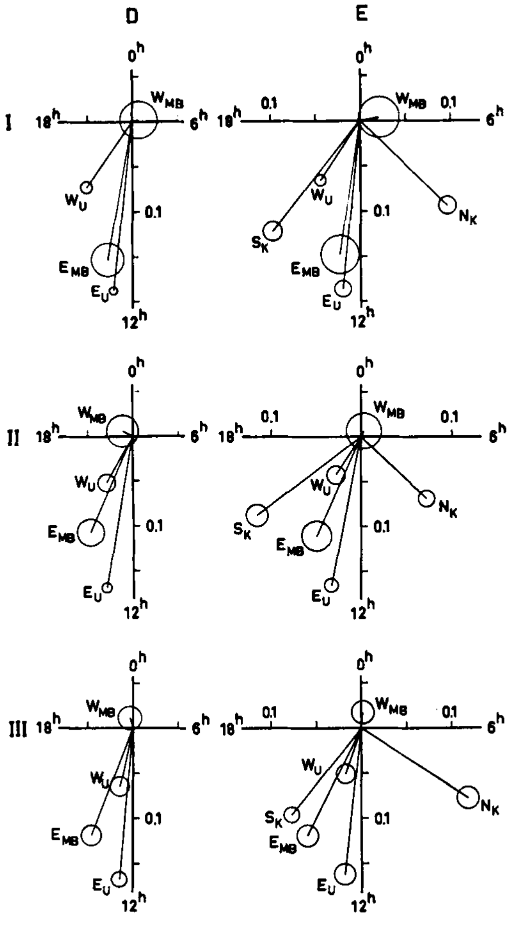

Fig. 3. Clock diagrams for the 12-monthly periods with identical days. For explanation cf. Table 1. I. Sept. 1, 1957 to Aug. 31, 1958. II. Calendar year 1958. III. May 1, 1958 to April 30, 1959.

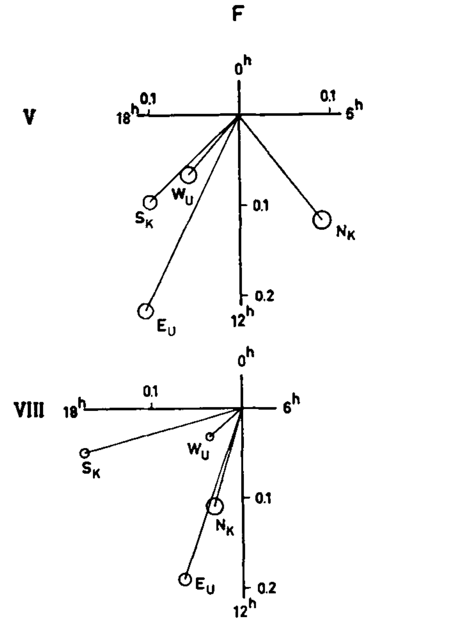

Fig. 4. Clock diagrams for the calendar years 1959 and 1960.

is the angle between the equatorial plane and the asymptotic direction, ψ the angle between the meridional plane through the point of observation and the projection of the asymptotic direction in the equatorial plane. These symbols will be employed for all the following discussions. In a preliminary paper (SANDSTRÖM, DYRING, LINDGREN, 1961) it has been shown that the amplitudes, corrected only for atmospheric pressure, appear to be proportional to the cosine of the latitude angle ϕ.

The short period vector sum diagrams

For reasons discussed in a preceding section, periods of shorter duration than one year are not employed as a main source of information in the present study. However, the 27-day means of the diurnal variation furnish some interesting evidence concerning the diverging character of the W_{MB} records (Figs. 5 to 7). Although of small importance for the discussion, it has to be remembered that, in this case, the diurnal vectors have not been derived from strictly identical days.

W_{MB} excepted all the vector sum diagrams are characterized by a constant trend. This is especially true concerning E_U. Very conspicuous phase changes are usually combined with small amplitudes. As a result the standard error of the phase becomes very big. However, the vector sum diagram for W_{MB} is completely different as compared to those for the other directions. It gives the impression of a random walk. At least in part this random walk character can be explained by the magnitude of the standard error as compared to that of the amplitude. The clock diagrams in Figs. 2 A and B as well as Fig. 3 show that as concerns W_{MB}, the standard error is equal to or even bigger than the amplitude. It follows that the standard error of the phase is considerable. However, this refers to 12-monthly means. Concerning the 27-day

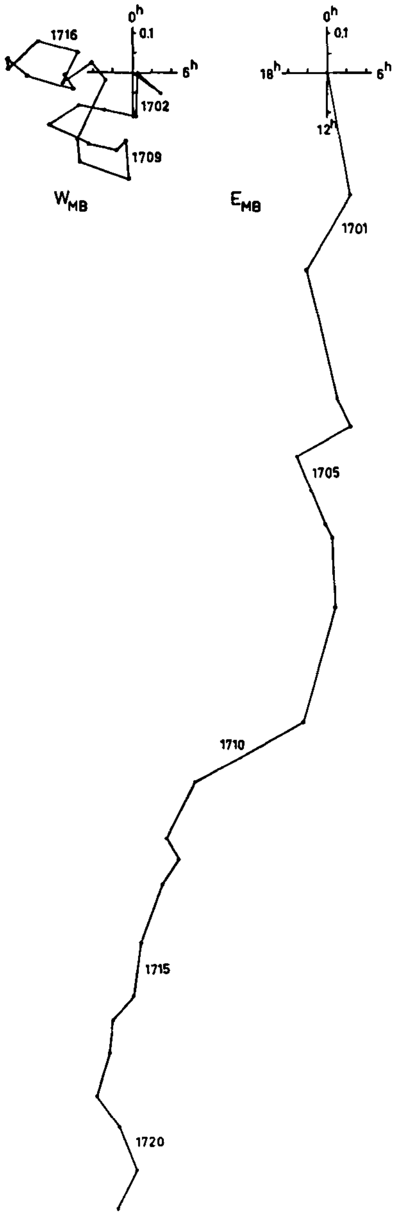

Fig. 5. Vector sum diagrams for the east- and west-pointing meson telescopes at Murchison Bay. The numbers refer to sun rotation periods according to Barthels.

periods the ratio between the standard error and the amplitude varies inside very wide limits. The standard error of the phase varies between 40 minutes and 6 hours. Not even twice the latter value would cover some of the phase shifts appearing in the W_{MB} short period records.

In September 1959 N_K and S_K suffered a major change as to phase (Fig. 6). As yet, the origin of this change has not been located. Fortunately, its influence on the present study can be found by comparing two consecutive 12-monthly periods (cf. p. 28).

The second harmonic

Concerning the peculiar features of the W_{MB} records there is one point which as yet has not been discussed. As can be gathered from Fig. 8, the distribution of the bihourly yearly means is of a magnitude inducing doubts even as to the existence of a true harmonic variation. For comparison the corresponding diagrams for the other five directions are included. The second harmonics have been computed simultaneously with the first harmonics. Concerning W_{MB} the amplitude of the second harmonic is almost of the same order of magnitude as that of the first harmonic.

It has been suggested that the second harmonic of the daily variation should be due to residual atmospheric effects. This is contradicted by the fact that for instance in 1958 the second harmonic of E_U had an amplitude exceeding the standard error by a factor 7 while the amplitude of W_U was only half as big as the standard error. It is very difficult to understand why any residual atmospheric effects would differ as concerns E_U and W_U, both sets of telescopes having the same zenith angles. In 1960 the second harmonic of W_U had a significant amplitude but it was still only one third of that of E_U.

Concerning the second harmonics of N_K and S_K the amplitudes display an irregular variation. All the 12-monthly means show a difference between the two directions far beyond what can be ascribed to statistical fluctuations. As concerns the 12-monthly means of E_{MB} and W_{MB} the amplitudes of the second harmonics are of the same order of magnitude as the standard errors.

Possibly the second harmonic is to be regarded only as a mathematical representation of semi-periodical perturbations, recognizable even in the yearly means. Such perturbations will certainly become very apparent in a case where the amplitude is small (W_{MB} in Fig. 8).

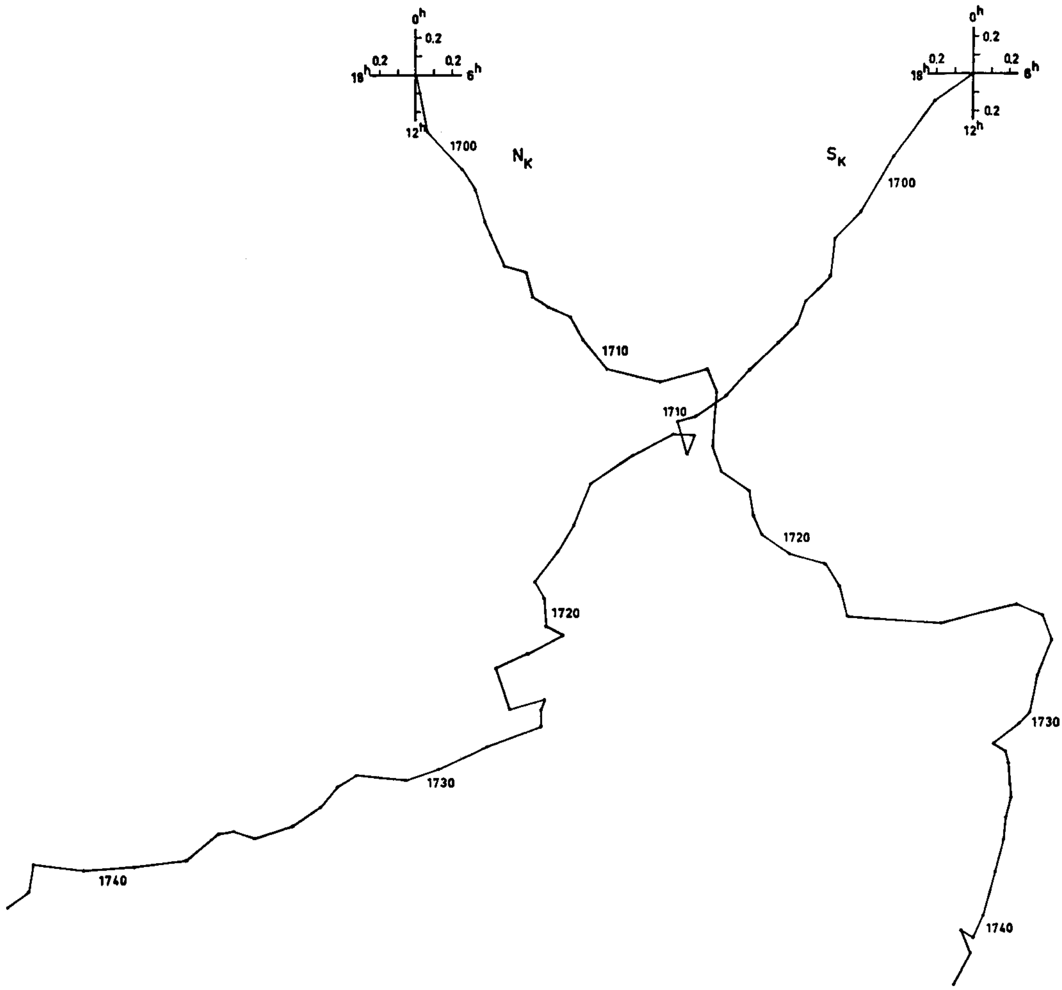

Fig. 6. Vector sum diagrams for the north- and south-pointing meson telescopes at Kiruna. The numbers refer to sun rotation periods according to Barthels.

Corrections for temperature effects

To the vectors in Figs. 2 to 4 other vectors have been added representing the yearly mean corrections for the variations in height and temperature at the 200 mb level. Existing direct measurements refer mostly to only two balloon flights a day (at 00 and 12 U.T.). This is insufficient for proper calculations of the phase. According to private communications from experienced meteorologists it is justified to put $13^h \pm 1^h$ L.T. the time of maximum.

ΔH_{200} being the amplitude of the variations in height of the 200 mb level and ΔT_{200} the temperature amplitude, the amplitude ΔR of the correction is given by the formula (LINDGREN, LINDHOLM, 1961):

$$\Delta R = \alpha_1 \Delta H_{200} + \alpha_2 \Delta T_{200}$$
$$\alpha_1 = (-3.6 \pm 0.5) \text{ per cent/km}$$
$$\alpha_2 = (-0.02 \pm 0.01) \text{ per cent/}^\circ\text{C}$$

Uppsala: $\Delta H_{200} = (20 \pm 3)$ m
Kiruna: $= (15 \pm 3)$ m
Murchison Bay: $= (10 \pm 3)$ m
$\Delta T_{200} = 0.5^\circ \pm 0.3$ for all the three stations.

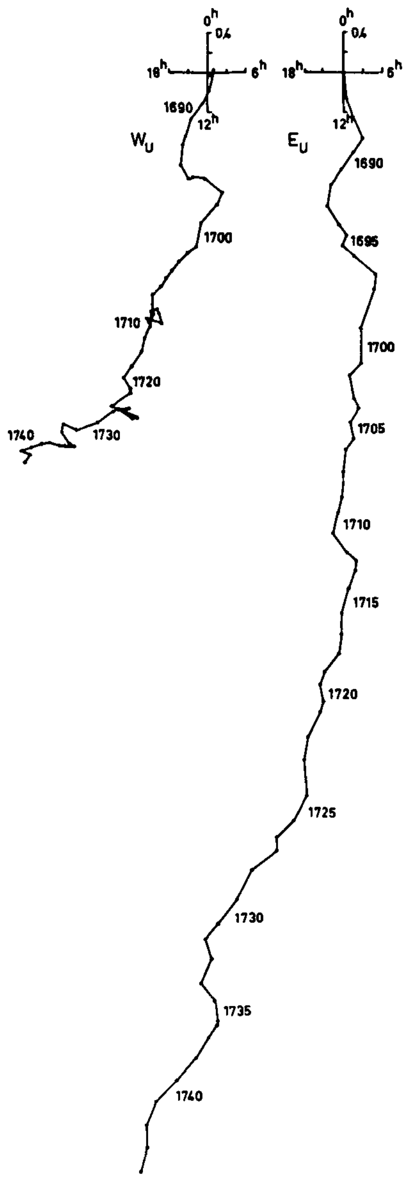

Fig. 7. Vector sum diagrams for the east- and west-pointing meson telescopes at Uppsala. The numbers refer to sun rotation periods according to Barthels.

The values of α_1 and α_2 were derived from the C.R. records obtained at Uppsala and Murchison Bay and contemporary aerological measurements. For Uppsala the latter relate to balloon flights from Bromma Airport, Stockholm. The values of ΔH_{200} were derived from one year's aerological records from Murchison Bay and two years' records from Bromma Airport. The value for Kiruna has been interpolated.

The temperature amplitudes estimated from the Uppsala and Murchison Bay records agree with values published by Rossi (1954) and Väisälä (1941). The errors of the amplitude and phase of the correction vectors are chosen large enough to cover even the variability from year to year during the period 1957–1960.

The corrected amplitudes and times of maximum are listed in Table 2. They are employed throughout the remaining part of this paper.

The correction for temperature effects make the phase as well as the amplitudes of W_{MB} significant despite the error increasing when the correction is applied. The time of maximum is in accordance with that of the other directions. The variations of the phase difference between N_K and S_K decrease also.

Evaluation of ψ and ϕ

An accurate determination of the direction of the anisotropy demands a thorough knowledge of the mean asymptotic directions to be associated with the axes of observation of the counter telescopes. The global curves of Brunberg furnish only the basic material for determining these directions. The as yet unknown rigidity spectrum of the anisotropy has to be taken into account. The influence of the atmosphere has also to be considered. The theoretical foundations for a complete calculation of the resulting acceptance cones for an instrument at sea level, as well as outside the earth's atmosphere, have been given by Brunberg (1958). Already from the global curve representation of the asymptotic directions (Brunberg, 1956) it can be gathered that the system of acceptance cones is complicated, especially as concerns telescopes with inclined directions. The calculations have turned out to be even more capacious than anticipated.

There is a very serious reason why the results of the present experiment have to be carried as far as possible prior to an accurate calculation of the mean asymptotic directions. Concerning the bulk of the radiation the number of particles entering the telescopes in a given direction is evidently independent of the corresponding asymptotic direction. However, if the anisotropy is concentrated to a region parallel with the earth's orbital plane, it can be regarded, in the laboratory system, as arriving from an

TABLE 2. *Amplitude and Phase Corrected for Temperature Effects.*

Cf. Table 1 for explanation of symbols. R = amplitude, t_{max} = time of maximum in U.T.

Period	E_U		W_U		N_K		S_K		E_{MB}		W_{MB}	
	R	t_{max}	R	t_{max}	R	t_{max}	R	t_{max}	R	t_{max}	R	t_{max}
I	0.269	1218	0.154	1306	0.185	954	0.210	1352	0.195	1226	0.048	1014
II	0.250	1230	0.127	1251	0.152	1006	0.191	1430	0.164	1311	0.040	1146
III	0.244	1218	0.134	1230	0.182	920	0.177	1344	0.175	1320	0.030	1200
IV	0.288	1246	0.161	1232	0.200	924	0.183	1336				
V	0.318	1318	0.161	1322	0.203	1014	0.189	1408				
VI	0.323	1248	0.140	1304	0.175	1048	0.203	1448				
VII	0.291	1318	0.128	1410	0.199	1236	0.228	1536				
VIII	0.280	1254	0.120	1311	0.176	1241	0.208	1550				

infinitely distant point source. Accordingly it is impossible to treat the excess radiation in the same simple way as the bulk of cosmic radiaation. The number of excess particles entering the telescope will depend on the latitude angle of the corresponding asymptotic direction. Accordingly, for a proper calculation of the intensity distribution between the successive acceptance cones for the inclined telescopes, it is necessary to know how the amplitude of the anisotropy varies with ϕ. Thus it becomes necessary to employ some empirical means of establishing, at least approximately, the desired function without resorting to a detailed calculation of the acceptance cones. The only possible way appears to be that of successive approximations starting with approximate values of the asymptotic directions.

To find the longitude correction ψ for the deviation of the primaries in the terrestrial magnetic field we apply the approximate method introduced by Brunberg (BRUNBERG, 1953*a*, BRUNBERG and DATTNER, 1954). Having identical zenith angles the two inclined telescopes in one and the same place are assumed to accept secondaries from primaries having the same effective rigidity. Originally Brunberg employed the same effective rigidity for all stations. With due regard for the distribution of the acceptance cones, this is too big an approximation. The effective rigidity has to be determined for each one of the stations separately.

Application of Brunberg's and Dattner's method gives the ψ values listed in Table 3. The corresponding ϕ values can be obtained from the global curves (BRUNBERG, 1956). They are listed in the same table together with the corresponding rigidity values. These values vary from one period to another. The values obtained by combining E_U and W_U differ considerably from those obtained by combining N_K and S_K. This fact emphasizes the importance of the relative positions of the acceptance cones.

TABLE 3. *Values of ϕ, ψ, and Effective Rigidity.*

Cf. Table 1 for explanation of symbols.

Period	ϕ						ψ						Effective rigidity GeV/c		
	E_U	W_U	N_K	S_K	E_{MB}	W_{MB}	E_U	W_U	N_K	S_K	E_{MB}	W_{MB}	U	K	MB
I	15°	81°	38°	51°	62°	67°	57°	47°	76°	17°	42°	75°	26	21	13
II	13°	76°	41°	50°	65°	67°	56°	52°	81°	15°	45°	64°	23	23	12
III	13°	74°	41°	50°	65°	67°	55°	54°	81°	15°	45°	64°	22	24	12
IV	12°	60°	39°	50°			52°	56°	79°	15°			18	22	
V	12°	72°	37°	51°			54°	55°	75°	17°			21	21	
VI	13°	75°	38°	51°			55°	53°	76°	16°			22	22	
VII	16°	81°	36°	52°			57°	46°	67°	22°			26	17	
VIII	13°	76°	36°	52°			56°	53°	68°	22°			23	18	

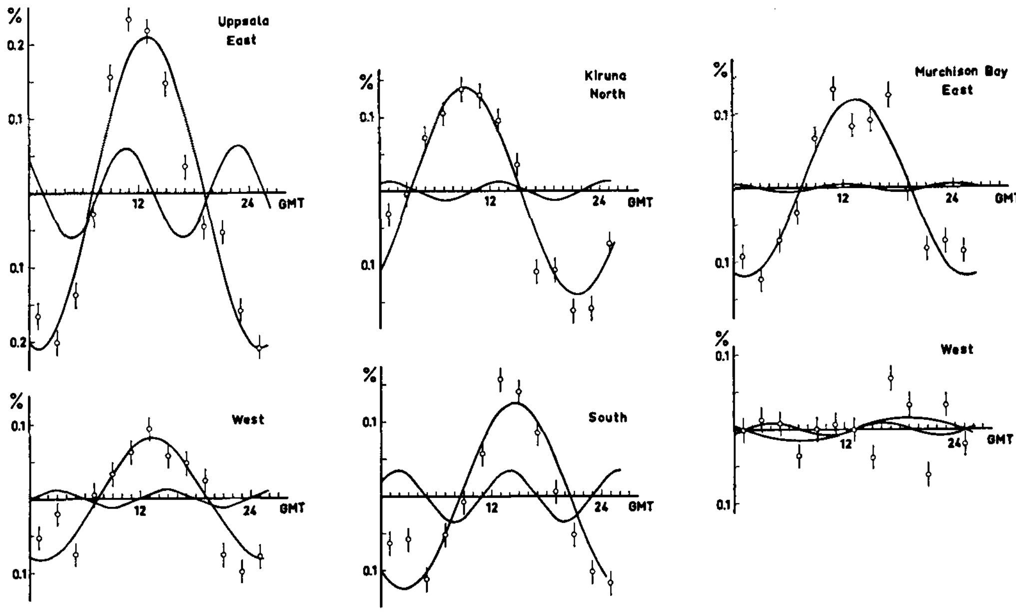

Fig. 8. First and second harmonics for the meson component recorded in the six directions employed to determine the direction of the anisotropy. 12-monthly periods.

It is also necessary to account for the longitudes of the recording stations. By addition of the longitude we get the direction of the anisotropy relative to the radius vector from the sun to the earth (Table 4). Considering the approximations the spread of the values is comparably small.

The values in Table 3 refer to identical days for all the six directions. It is a matter of opinion if it would not be better to employ averages over all available days to determine the angles ψ and ϕ as well as the effective rigidity. This has been done for the data corrected only for atmospheric pressure. The results did not differ, outside the standard errors, from the corresponding values relating to identical days (SANDSTRÖM, DYRING, LINDGREN, 1961). The addition of the correction vector will not change this fact.

TABLE 4. *The Angle Between the Direction of the Anisotropy and the Earth–Sun Line.*

Period	Uppsala	Kiruna	Murchison Bay	Mean
I	78°	60°	63°	67°
II	80°	68°	77°	75°
III	76°	56°	80°	71°
IV	79°	55°		67°
V	90°	64°		77°
VI	83°	73°		78°
VII	91°	91°		91°
VIII	85°	94°		90°

Comparing periods VII and VIII with period V (Tables 1 and 3) we find that the prominent phase changes displayed by N_K and S_K in Sep. 1959 (Fig. 6) correspond to a considerable decrease in the effective rigidity. The significance of this fact is obscure. However, concerning the ϕ-values the corresponding change does not exceed the magnitude of the variations during the preceding periods. The ψ-values suffer a bigger change (compare p. 24). The phase changes of W_U (Fig. 7) appears to be of no importance as concerns ϕ or ψ.

The very low values of the effective rigidity for Murchison Bay are probably due to the well defined focussing point for rigidities less than 10 GeV/c (ÅSTRÖM, 1958).

Depression of the amplitudes through the spread of asymptotic directions

The diurnal variation becomes partly smoothed out by the spread of the ψ-values over a wide region. This effect is very prominent in the equatorial region (Figs. 4–5 and 18–23, Brunberg, 1956). It is less pronounced in intermediate and high latitudes. In the latter case the existence of focussing points constitutes a counteracting effect (Åström, 1958).

Concerning the directions employed for the present study the curves for ψ and ϕ (Figs. 15, 30, 31, and 32, Brunberg, 1956) reveal that the spread of the ψ-values is comparatively small for E_U, E_{MB}, and S_K. As concerns W_{MB} a considerable part of the symptotic directions cover the polar region. A daily variation is to be expected only because of the existence of a focussing point ($\psi \approx 57°$; $\phi \approx 65°$).

A correction for the influence of the spread of the asymptotic directions involves the same difficulties as the calculation of the mean asymptotic directions. Instead, an effort has been made to evaluate the maximum errors introduced by neglecting such a correction. For that purpose certain assumptions had to be made.

The anisotropy was assumed to be constant for rigidities less than 100 GeV/c and negligible for rigidities above this value.

The multiple scattering in the atmosphere and the variation of the amplitude with ϕ were neglected.

The cut off rigidity was assumed to be 6 *GeV/c* (Dorman, 1957). This value appears reasonable also because of experiences gathered from solar flare effects.

The error was calculated for directions of observation outside the atmosphere corresponding to the existing curves of ψ and ϕ (Brunberg, 1956). The angular distribution of the mesons as a function of the primary rigidity was calculated according to theory (Bradt, Kaplon, and Peters, 1950). The C. R. rigidity spectrum was assumed to be described by

$$N(\varepsilon) \approx \varepsilon^{-2.5},$$

where ε is the primary energy. The meson multiplicity was made proportional to ε.

It is also necessary to account for the influence of the geometry of the meson telescopes and for the probable instrumental cut offs for secondaries of primaries penetrating into the atmosphere from the considered directions. This was done by varying the relative amounts with which the separate directions could be supposed to contribute to the smoothing out effect. W_{MB} excepted, the errors were found to be rather insensitive to the relative "intensities" thus ascribed to the directions of the primaries.

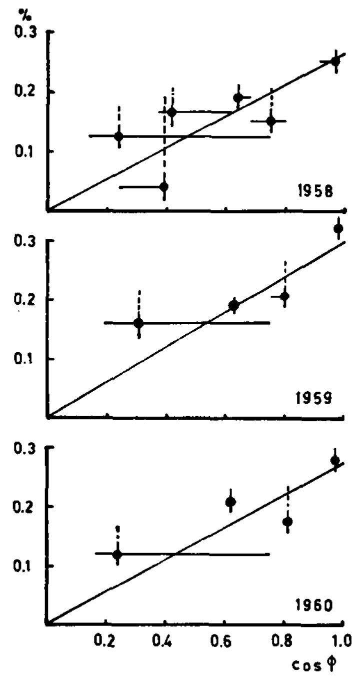

Fig. 9. The amplitude as a function of cos ϕ. In the 1958 diagram the directions are in order from left to right: W_U, W_{MB}, E_{MB}, S_K, N_K, E_U. In the 1959–60 diagrams they are: W_U, S_K, N_K, E_U.

As concerns E_U and S_K the errors turned out to be negligible. The observed amplitude of E_{MB} might be 10 per cent too small and those of N_K and W_U as much as 20 per cent too small. The amplitude of W_{MB} is badly defined. Possibly the observed value is 200 per cent too small.

The amplitude as a function of the asymptotic direction

Proceeding to the amplitude as a function of ϕ we start by assuming that it is proportional to cos ϕ. This assumption is based on the model under consideration, i.e. the flow of excess particles being parallel to the orbital plane of the earth. In Fig. 9 the amplitudes have been plotted against cos ϕ.

The errors in ϕ are due mostly to the errors in the correction for temperature effects. In each case the corresponding error in ϕ depends on the gradient of ϕ as a function of rigidity. As a result, the errors in the positive and negative directions sometimes differ as to magnitude. From the global curves (Figs. 30–32, BRUNBERG, 1956) and the rigidity values in Table 3 can be seen that the points for W_U, E_{MB}, and W_{MB} are to be found on very unfavourable parts of the curves. In some other cases the error is covered by the filled circle marking the point.

Also concerning the amplitudes, part of the error is due to statistical fluctuations and errors in the correction for atmospheric effects. In Fig. 9 this part is marked by full drawn lines. The added broken lines indicate errors due to the absence of a correction for the smoothing out of the diurnal variation. This error is always of positive sign.

The calendar years 1958, 1959, and 1960 have been selected for the presentation of the results (Fig. 9). The lines are drawn according to closest fit with the added condition of their passing through origo. With due regard for the errors, the points fit the lines. E_U 1959 and S_K 1960 are displaced more than the indicated errors. However, a correction for the depression of the amplitude will shift the points corresponding to N_K upwards. The fit will then become good in these cases too.

For the three calendar years the diagrams give in order 0.26, 0.30, and 0.27 per cent as the yearly mean amplitudes of the anisotropy in the equatorial plane. The variation is not significant. At the present stage it can be regarded as a measure of the error. For the purpose of comparison the amplitude of W_{MB} was calculated from these values. Including the cos ϕ dependence the same principles were followed as in the evaluation of error due to the smoothing out effect. The calculated value is (0.039 ± 0.004) per cent in good agreement with the W_{MB} values for the partly overlapping periods I, II, and III (Tables 1 and 2). Consequently we may conclude that the error, appointed to the amplitude of W_{MB}, has become too big by our neglecting the cos ϕ dependence.

The direction of the anisotropy in the orbital plane of the earth

The corrected directions ought to be the same regardless of the station. However, the values in Table 4 reveal discrepancies between the corrected directions as obtained from the pairs $E_U - W_U$ and $N_K - S_K$. This is illustrated by the clock diagrams in Fig. 10. The errors are insignificant in comparison with these discrepancies. The limits of error are indicated by figures distinguishing them from the circles usually employed for standard errors. The main part of the error in the phase is due to the limited accuracy of the correction for temperature effects. The standard error becomes important only as regards W_{MB}. As concerns the amplitudes the limits of error do not include the systematic error due to the spread of the asymptotic directions. On the whole, the absolute values of the amplitudes do not enter into the discussion of the yearly mean direction in the equatorial plane.

Considering that the ψ-values represent an approximation the discrepancies might be due to this cause alone. It is therefore natural to use the mean of the values derived from each pair of directions. These are listed in the last column of Table 4. It has to be remembered that the difference between the yearly mean directions of E_U–W_U and N_K–S_K during 1959 might be due to the big phase changes suffered by the two Kiruna directions in September that year (Fig. 6). According to Table 3 this event results in a shift of the ψ-values. It is remarkable, however, that the agreement is good for the two sets of directions during 1960 although the phase difference between N_K and S_K then differs markedly from that during 1958 (compare also Table 2).

The vectors representing the mean yearly amplitudes in the equatorial plane have been plotted in Fig. 11. Judging from the 1959 diagram (Fig. 10) the errors can be estimated to $\pm 20°$. From this diagram as well as the values in Table 4 it appears as if the direction of the anisotropy has varied in a systematic way from 1957 through 1960. This would be in agreement with previous experiences (ELLIOT and THAMBYAHPILLAI, 1953, BRUNBERG and DATTNER, 1954). However, the limits of error are too big for any definite conclusions to be drawn. If, instead, this variation is regarded as an indication of the approximate nature of the values of the longitude correction ψ, we arrive at the conclusion that the yearly mean direction of the anisotropy is at right angles to the earth–sun line.

Conclusions

1. The yearly mean amplitudes fit the curve $R \cos \phi$, where R is the amplitude in the equatorial plane and ϕ the latitude angle of the mean asymptotic direction. This is a proof of the yearly mean anisotropy being at least approximately parallel to the orbital plane of the earth.

2. During the period Sep. 1, 1957–Dec. 31, 1960 the direction of the flow of excess particles, responsible for the anisotropy, made an angle of close to 90° with the earth–sun line, the flow of excess particles overtaking the earth from the afternoon side.

3. The direction of the anisotropy is in accordance with a model of the diurnal variation proposed by ALFVÉN (1954).

4. The yearly mean amplitude of the anisotropy is ± 0.28 per cent.

5. In certain instances the latitude angle ϕ is very sensitive to small changes in the phase difference between the two inclined directions at one and the same station. This fact reduces the value of some directions, for instance W_U, E_{MB}, and W_{MB}. Although the error originates in the statistical fluctuations and above all, in the limited accuracy of the correction for temperature effects, it increases in magnitude and gains its asymmetrical character through the method of establishing the values of ψ and ϕ. Accordingly, the importance of the affected directions will be restored when proper calculations become available of the acceptance cones for inclined directions.[1]

6. The above conclusions concerning the direction of the anisotropy are at variance with previous results by ELLIOT, and ROTHWELL (1956). At present it appears impossible to account for this contradiction. However, their investigation comprised only two directions at one station. The shifts of phase displayed by the two Kiruna directions show that it is dangerous to draw conclusions from one station alone. It has to be emphasized that in the present case the biggest amplitude always is recorded by the east-pointing telescopes in Uppsala, i.e. in a direction approximately parallel to the equatorial plane.

[1] According to private communications from Dr. E.-Å. Brunberg these calculations will be completed in the near future.

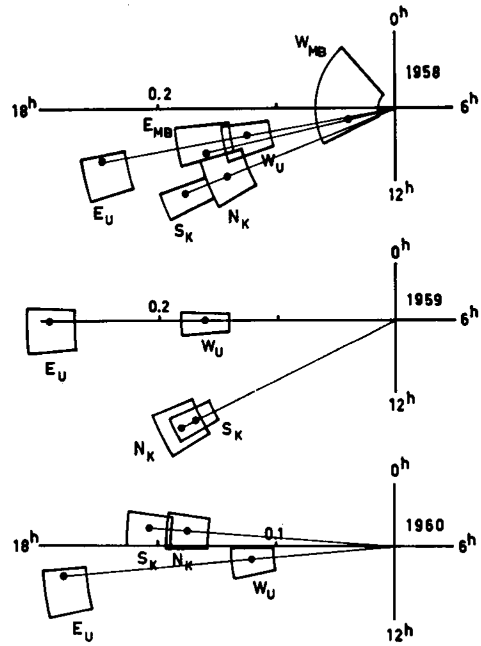

Fig. 10. The diurnal variation corrected for the longitudes of the stations and the deviation of the primaries by the terrestrial magnetic field.

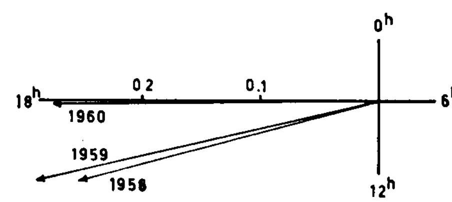

Fig. 11. Direction and magnitude of the anisotropy in the orbital plane of the earth.

7. For very good reasons it can be assumed that even during short periods the anisotropy is to be found in a direction parallel to the orbital plane. The components which have been proposed until now are mostly of a character making this assumption natural (SANDSTRÖM, 1956, 1958; DATTNER and VENKATESAN, 1959).

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